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OFFICE OF AERONAUTICS, EXPLORATION AND TECHNOLOGY

TRANSPORTATION TECHNOLOGY PROGRAM
STRATEGIC PLAN

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EXECUTIVE SUMMARY

Since the beginning of the space program, there has been a need to conduct research and to develop new technology. Unfortunately, funding constraints have limited efforts within the space program. As foreign space programs develop and expand, the lack of an adequate research and development program has led to concerns that the U.S. may soon lose its technological edge. This has led to an emphasis on technology both within and outside of the NASA.

AUGUSTINE COMMITTEE

In December 1990, the Report of the Advisory Committee on the Future of the U.S. Space Program was issued. On pages 47 & 48 of the report, the committee summarized its findings with regard to NASA space goals (five principal elements) and NASA programs (five recommendations), as well as affordability (three recommendations) and management (seven recommendations). Significant emphasis was placed by the committee on technology. For example, of the five principal elements, which the committee recommended as the balanced set, the following was included:

A significantly expanded technology development activity, closely coupled to space mission objectives, with particular attention devoted to engines (Recommendation 8).

Similarly, the committee's recommendations concerning NASA programs again restated the need for a new technology program as follows:

A revitalized technology plan be prepared with strong input from the mission offices, and that it be funded (also part of Recommendation 8).

SPACE TRANSPORTATION

Any space program is dependant on its ability to launch men and equipment into space, as well as to move around in space. A basic requirement for a successful space program is available, reliable, and affordable (i.e. competitive) transportation for the broad range of science, exploration, environmental, commercial and national security missions. Thus, space transportation is a key element not only of the space program, but also of the space technology program. This theme was stated in the new National Space Launch Strategy issued by the Vice President in July 1991 as follows:

- (1) Ensuring that existing space launch capabilities, including support facilities, are sufficient to meet U.S. Government manned and unmanned space launch needs*
- (2) Developing a new unmanned, but man-rateable, space launch system, to greatly improve national launch capability with reductions in operating costs and improvements in launch system reliability, responsiveness, and mission performance.*
- (3) Sustaining a vigorous space launch technology program to provide cost effective Improvements to current launch systems, and to support development of advanced launch capabilities, complementary to the new launch system*

- (4) *Actively considering commercial space launch needs and factoring them into decisions on improvements in launch facilities and launch vehicles...*

OFFICE OF AERONAUTICS, EXPLORATION AND TECHNOLOGY (OAET)

NASA has chartered OAET to define the technology program required to meet the transportation technology needs for current and future civil space missions. OAET has established a focused thrust within the Civil Space Technology Initiative (CSTI) for each of the critical technology areas. This report deals with the Space transportation focused thrust. The Transportation Technology Team formed by OAET Director of Space Technology consists of senior representatives from Marshall Space Flight Center (MSFC), Johnson Space Center (JSC), Kennedy Space Center (KSC), Langley Research Center (LaRC), Lewis Research Center (LeRC), Jet Propulsion Laboratory (JPL) and the Headquarters Office of Space Flight (OSF). A space transportation specialist from an OAET Space Technology contractor, General Research Corporation (GRC), assisted in the team activities. This team is co-chaired by the NASA Headquarters Assistant Director for Space Technology (Transportation Systems) and by the MSFC Director for Research and Technology.

PROCESS

The following process was developed to bring together the technology community and the user communities:

DEFINE THE USER COMMUNITY: The Office of Space Flight (OSF), the Office of Space Science and Applications (OSSA), the Office of Space Operations (OSO) and the newly formed Office of Exploration as well as the aerospace industrial community including the commercial space transportation industry.

DEFINE TECHNOLOGY GOALS: To provide vehicle systems technologies that substantially improve safety and reliability, increase system availability and provide new capabilities and improved performance while reducing life cycle costs.

DEFINE TECHNOLOGY OBJECTIVES:

- Enhance existing manned launch systems
- Develop technologies for a new manned systems
- Develop technologies for robust, low-cost follow-on unmanned launch systems and heavy-lift launch systems.
- Develop and transfer low-cost technology to support commercial unmanned launch vehicles.
- Develop and transfer technologies to enhance current performance of upper stages and to enable new approaches for higher Earth orbit missions.
- Develop technologies to enable low-cost, high-performance, and reliable cargo and personnel transport in space for Lunar and Mars applications.
- Demonstrate technologies and collect critical flight research data through the implementation of in-space technology flight experiments that support all vehicle systems.

ESTABLISH A VISION OF FUTURE SPACE TRANSPORTATION NEEDS:

The sub-system technology needs can also be based on an aggressive view of future transportation needs. The following aggressive vision ensures that

technology enables (rather than limits) future systems:

The Space Shuttle will be upgraded to provide personnel transport well into the next century.

A Personnel Launch System (PLS) will be developed to provide complementary access to space during the Space Shuttle lifetime.

An Advanced Manned Launch System (AMLS) will be developed to provide for a long-term replacement for the Shuttle.

Existing ELVs will be upgraded as required to provide cargo transport.

A National Launch System (NLS) will be developed to provide enhanced capability to transport cargo and the Personnel Launch System.

Current upper stages for ELVs and Shuttle will be upgraded to enhance performance and reliability.

New upper stage(s) will be developed as a part of the National Launch System.

A heavy-lift upgrade of the National Launch System (capability in the multi-hundred-ton class) will be developed for practical implementation of the Space Exploration Initiative.

Transfer vehicles and landers necessary for the exploration of our Moon and Mars and to sustain space-based operations will be developed for implementation of the Space Exploration Initiative.

ESTABLISH THE USER REQUIREMENTS: Specific technology requirements (subsystem needs) were provided by the user community. The Office of Space Flight (OSF) has responsibility for Earth-to-Orbit transportation (both Space Shuttle and Expendable Launch Vehicles). OSF technology needs were those judged likely to have a high payoff for those NASA systems. The Office of Space Science and Applications (OSSA) has responsibility for Life Sciences, Earth Science, Solar System Science, Microgravity, Space Physics, and Astrophysics. OSSA needs were for propulsion and automated systems technologies. The Office of Space Operations (OSO) has responsibility for development and operation of ground and space systems for tracking, data acquisition and management, and telemetric navigation. The OSO requirements focused on advanced navigation technologies. The newly formed Office of Exploration (OE) is responsible for developing strategies for the Space Exploration Initiative. The OE technology needs were either enabling or high-leverage technologies in the propulsion area. The commercial space transportation industry technology requirements were extracted from Aerospace Industries Association (AIA), National Research Council (NRC), and Department of Transportation (DOT) Commercial Space Transportation Advisory Committee (COMSTAC) sources. These requirements focused on high-leverage cost-reduction technologies. Continuing dialogues with the space launch industrial community will be employed to more accurately determine specific commercial ELV technology requirements.

ESTABLISH TECHNOLOGY REQUIREMENTS: A list of technology requirements was developed by combining the user subsystem requirements and the subsystem requirements that enable the vision of future space transportation needs. The individual requirements were compiled and evaluated to establish a single priority list.

IDENTIFY EXISTING TECHNOLOGY EFFORTS: On-going focused technology programs were identified in propulsion (both chemical and nuclear), cryogenic fluids management, avionics and aerothermodynamics. Also an OAET Space R&T Base program effort was identified in propulsion, aerothermodynamics, cryogenic fluids, avionics, and artificial intelligence and robotics.

DEFINE THE NEW TECHNOLOGY PROGRAM: A new work breakdown structure (WBS) was defined for transportation-related technology research. The existing programs and the new proposed programs were segmented into the three technology areas:

- Earth-to-Orbit Transportation (necessary to provide access to low Earth orbit (LEO)):
 - Earth-to-Orbit Propulsion (Existing)
 - Earth-to-Orbit Structures and Materials
 - Earth-to-Orbit Vehicle Avionics
 - Low-Cost Commercial Transport
 - Auxiliary Propulsion (Potential Future)
- Space Transportation (necessary to provide access beyond LEO):
 - Advanced Cryogenic Engines (Existing)
 - Nuclear Thermal Propulsion (Existing)
 - Nuclear Electric Propulsion (Existing)
 - Aeroassist /Aerobraking (Funded through FY 91)
 - Cryogenic Fluids (Funded through FY 91)
 - Autonomous Landing (Funded through FY 91)
 - Autonomous Rendezvous and Docking (Funded through FY 91)
 - Transfer Vehicle Avionics
 - Transfer Vehicle Structures and Materials
- Technology Flight Experiments (necessary to provide validation which could not be achieved otherwise)
 - Aeroassist Flight Experiment (Existing)
 - Cryogenic Orbital Nitrogen Flight Experiment
 - Solar Electric Propulsion System Flight Experiment
 - Cryogenic Orbital Hydrogen Flight Experiment (Potential Future)
 - High Energy Aerobraking Flight Experiment (Potential Future)

DEVELOP BRIDGING PROGRAM / INTERNAL REVIEWS: This plan addresses the development of immature technologies and does not focus on advanced development programs needed to carry proven technologies to readiness.

Agency technology working groups are being developed to help "bridge" technology maturation gaps between OAET and the user organizations. In the area of avionics, the process began with the Strategic Avionics Technology Working Group (SATWG), initiated at Williamsburg in November 1989. In propulsion, the Space Propulsion Synergy Group is growing out of the 1990 Penn State Symposium. In structures and materials, a workshop is planned for September 1991.

EXTERNAL REVIEWS: In June of this year, the Space Systems & Technology Advisory Committee, The SSTAC Aerospace R&T Subcommittee, the National Research Council Aeronautics and Space Engineering Board, and selected individuals from the Space Science and Applications Advisory Committee, the Aerospace Medicine Advisory Committee, the NRC Space Studies Board, the Department of Defense, the Department of Transportation, the Department of Commerce, the Department of Energy and the Aerospace Industries Association convened at Vienna, Virginia to review the OAET Space R&T Integrated Technology Program. The figure below illustrates the FY 1992 budget request run-out contrasted with the "3X" budget target and the funding required to fully implement the strategic plan.

PUBLISH PLAN: The plan establishes a baseline for the Space Transportation Technology Thrust. The Transportation Technology Program Plan is a strategic plan. It attempts to address all of the critical technology needs.

ESTABLISH YEARLY UPDATE / REVIEW CYCLE: The plan will be published yearly with an addendum being published after the President has presented his FY 1993 budget to the Congress in February, 1992. At that time, the Transportation Technology Team will add an addendum to this report that includes the FY 1993 budget with its runout as it pertains to the Transportation Technology Program as well as the actual FY 1992 program.

As this document goes to press, several significant events have been or are about to be announced. These events include a conference committee in Congress finalizing the NASA FY 1992 budget for the President's signature, the announcement of the formation of a new Office of Exploration, another announcement naming a new Office of Space Systems Development and a revised definition of roles and missions for the various NASA Centers expected to be announced in the near future by the Associate Administrator. These changes will be reflected in an updated plan which should be released by late summer 1992 and will include a proposed FY 1994 program plan. It will also reflect user requirement updates expected from the OSSA Woods Hole meetings this summer and any changes to the SEI technology needs as necessitated by the resolution of any differences between the Synthesis Group and the current Office of Space Exploration as well as any deltas that may be introduced by the recently announced Office of Exploration to be organized in the coming weeks or months. This report refers to FY 1991 programs as "Current Programs".

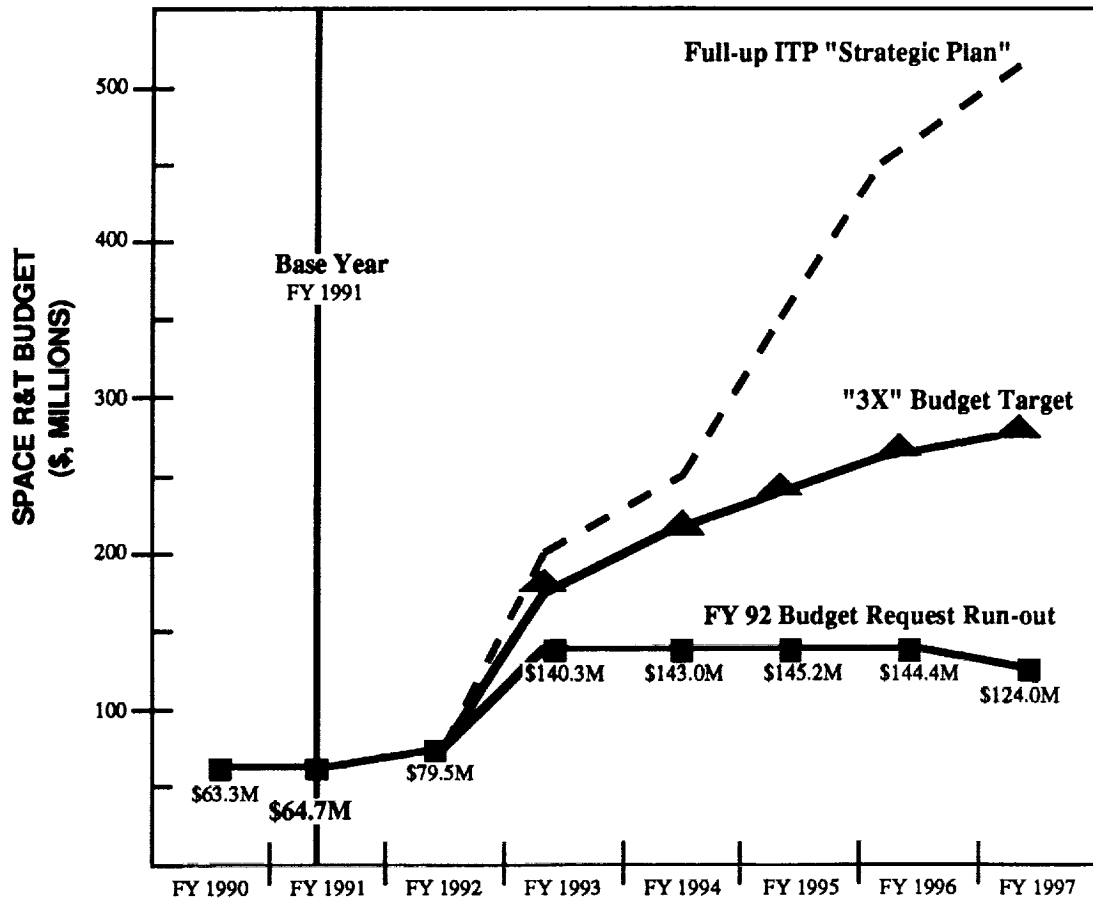
PAYOFFS

- A broadly based research and focused technology program to support long-term improvements in national space launch capabilities;
- Retaining and expanding the technology lead of the U.S. in the Space Transportation area;

- Enhanced U.S. Commercial Space Launch capabilities; and
- Revitalization of the U.S. technology base.

To fully implement this strategic plan is clearly beyond the NASA Space R&T fiscal resources. Therefore, one purpose of this plan is to serve as a mechanism for coordination with other government and industry plans to synergistically pursue technology development in areas of common interest.

TRANSPORTATION TECHNOLOGY BUDGET IMPLICATIONS



CHAPTER 1

INTRODUCTION

1.1 Purpose and Objectives

The purpose of this report is to define the technology program required to meet the transportation technology needs for current and future civil space missions. It is a part of an integrated plan, prepared by NASA in part in response to the Augustine Committee recommendations, to describe and advocate expanded and more aggressive efforts in the development of advanced space technologies. This expanded program will provide a technology basis for future space missions to which the Nation aspires, and will help to regain technology leadership for the U.S. on a broader front. The six aspects of this integrated program / plan deal with focused technologies to support *Space Sciences, Exploration, Transportation, Space Platforms and Operations* as well as provide a *Research and Technology Base Program*. This volume describes the technologies needed to support Transportation Systems, e.g., technologies needed for upgrades to current transportation systems and to provide reliable and efficient transportation for future space missions.

The Office of Aeronautics, Exploration and Technology (OAET) solicited technology needs from the major Agency technology users and the aerospace industry community and formed a Transportation Technology Team (Appendix A) to develop a technology program to respond to those needs related to transportation technologies. This report addresses the results of that team activity. It is a strategic plan intended for use as a planning document rather than as a project management tool. It is anticipated that this document will be primarily utilized by Research & Technology (R&T) management at the various NASA Centers as well as by officials at NASA Headquarters and by industry in planning their corporate Independent Research and Development (IR&D) investments.

1.2 Background

In mid-1990, NASA formed a group to develop a long range plan for space technology development (the Space R&T Long Range Planning Committee). This plan was to be used for advocacy, budget planning, support for internal planning processes, and for communication / coordination within the Agency. In early 1991, adjustments were made in this objective, and the Group was commissioned by the NASA Administrator to develop and Integrated Technology Plan in response to two of the recommendations from the December 1990 Report of the Advisory Committee on the Future of the U. S. Space Program (the Augustine Committee).

Within this framework, OAET has the responsibility for the development of space technology. OAET's mission statement states that:

OAET shall provide technology for future civil space missions and provide a base of research and technology capabilities to serve all national space sectors.

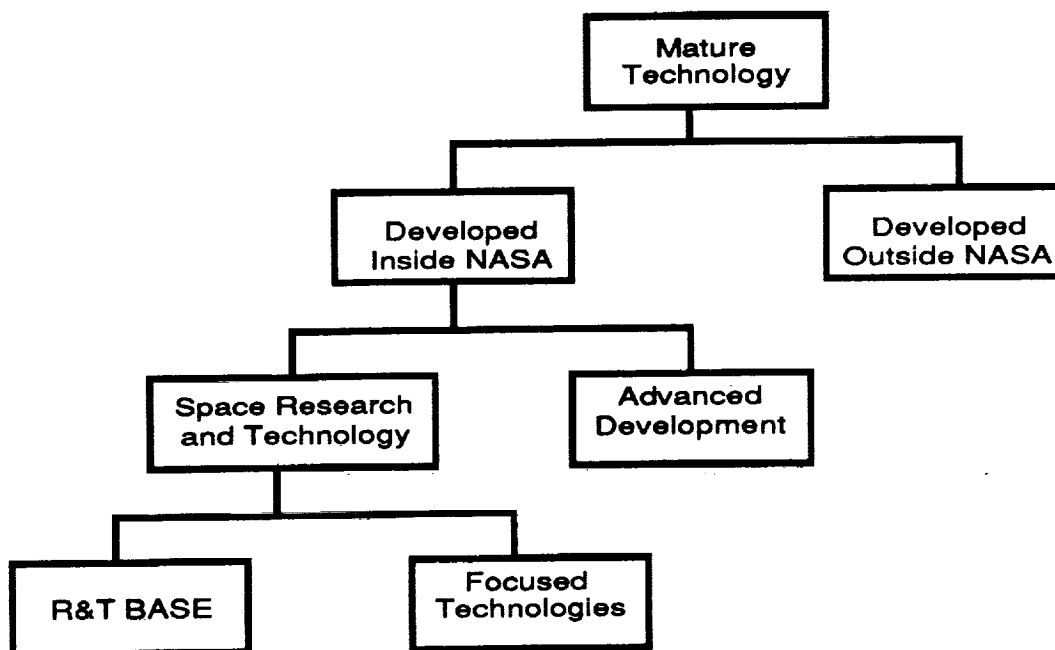
This mission statement leads to the OAET specific goals of:

- *Identifying, developing, validating, and transferring technology to:*

- *Increase mission safety and reliability*
 - *Reduce program development and operations costs*
 - *Enhance mission performance*
 - *Enable new missions*
- *Providing the capability to :*
 - *Advance technology in critical disciplines*
 - *Respond to unanticipated mission needs*

To achieve these goals, OAET conducts the Space Research and Technology (SR&T) Program which consists of a continuum of space research and technology activities ranging from initial research conceptualization to selective full-scale test of prototype equipment in space. Initial research on new technologies is conducted within its R&T Base Program while development of those technologies to a more advanced phase is carried out within the Focused Technology Program. In some cases, the flight testing of the technology will be accomplished by OAET. In most cases however, the final development of a technology for a specific application will be done by other parts of NASA as part of their Advanced Development effort. The technology development process is schematically depicted in Figure 1-1.

Figure 1-1
TECHNICAL DEVELOPMENT



Activities include work that is performed by in-house staff at the NASA Centers, University researchers supported by NASA-funded grants and contracts, and industrial aerospace organizations under contract to NASA. These diverse activities provide evolutionary advances in technology in all significant space disciplines to meet current and future mission needs as well as technology breakthroughs that may revolutionize a technical discipline or mission concept. The work is managed and coordinated by OAET through a

process that integrates the best available talent and capability in NASA, industry, and universities into a national civil space research and technology program.

Technology development within the Space R&T Program is driven by user needs (that is, the requirements of other NASA program offices and the commercial space industry), and is aimed at meeting those needs that are currently identified, and developing a technology base to meet needs expected to surface in the future. The Program is also designed to develop capabilities and opportunities that may not yet be perceived as needed by potential users. This latter function is vested in the area of work within the Research and Technology Base Program while the former function is carried out through focused technology programs.

There are five discipline areas within the R&T Base, which develops new technology. These are: Aerothermodynamics, Space Energy Conversion & Propulsion, Materials & Structures, Information Controls & Human Support, and Advanced Communications. In the Focused Technology Programs, the five technology programs correlate with the major organizational and mission orientations of NASA. Each focused technology program responds to a major area of NASA's strategic interests. The focused technology programs are: Space Science, Exploration, Transportation, Space Platforms and Operations.

Space Science Focused Technology program provides technology needed for future space science missions. Space Exploration Focused Technology Program provides the technology (except transportation) for future missions to Mars and the Moon. The Transportation Focused Thrust provides technology for improvements and development of all transportation needs. The Space Platforms Focused Thrust provides the technology needed for future space platforms. The Operations Focused Thrust provides technology for improvements in all operations.

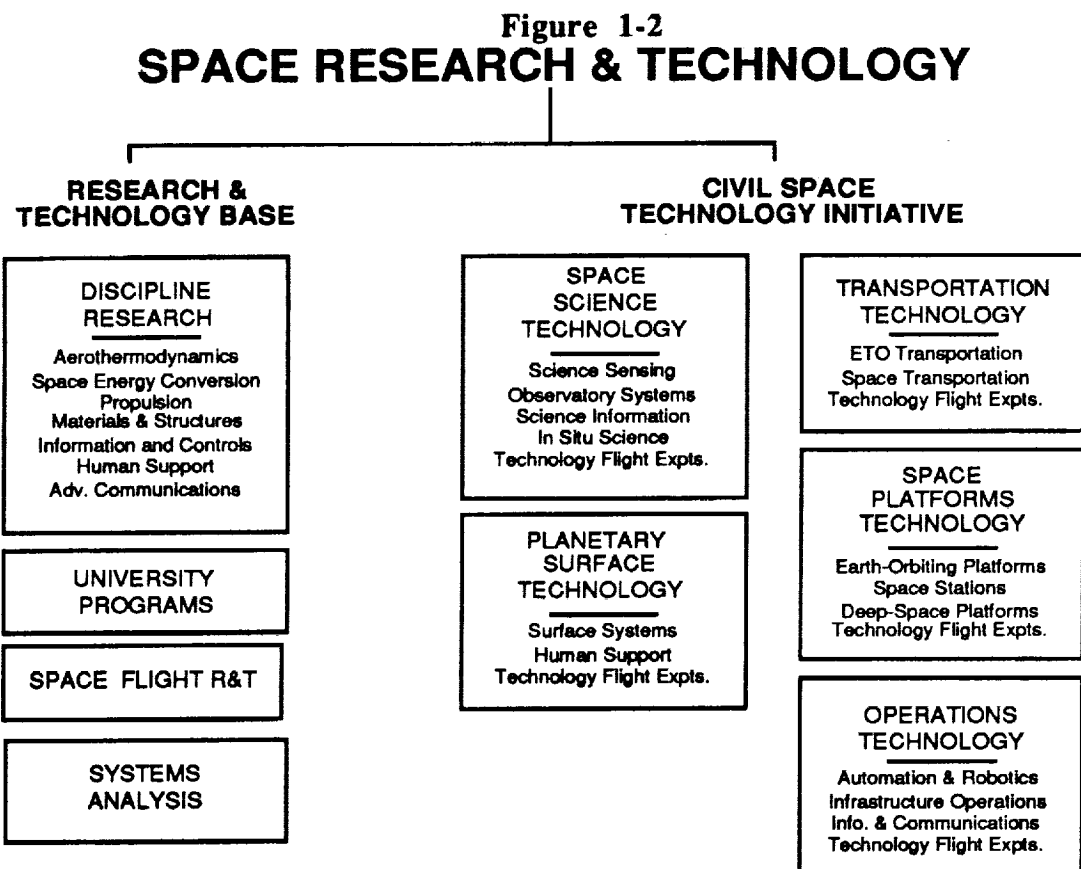
The Overall Integrated Technology Plan report is being prepared (due in November 1991) and will give an overview of the total plan and describes the planning and independent review process. This report, written before Congress has completed finalization of the FY1992 budget for the President's signature, refers to FY 1991 programs as "current" and focuses on the Transportation Technology program and the supporting Research & Technology Base programs.

1.3 Scope

This report addresses the most critical civil space transportation technology needs identified by the user communities served by OAET and describes the current and proposed OAET programs that meet these needs. The user communities served by OAET are NASA program offices, primarily the Office of Space Flight (OSF), the Office of Space Science and Applications (OSSA), the Office of Space Operations (OSO) and the newly formed Office of Exploration as well as the aerospace industrial community including the commercial space transportation industry. OSF programs include the Space Transportation System (STS), the Space Station Freedom Program (SSFP), and Flight Systems (FS). The user community relies on a wide range of transportation systems to achieve their goals and objectives.

The Space R&T program includes two basic elements, as are shown schematically in Figure 1-2. The "Focused Technology" programs are geared to meet the identified needs of user agencies. The "Research & Technology Base" program engages in more basic technology undertakings, to develop capabilities and opportunities that may not yet be perceived as needs by the user organizations. The former category (focused technology

programs) is the principal subject of these reports and plans. In the discussions and descriptions of the focused technology program in the succeeding sections, relationships to current and planned activities in the R&T Base program will be noted.



This report addresses the development of immature technologies and does not focus on advanced development programs needed to carry proven technologies to readiness. However, bridging activities intended to identify opportunities for introducing new technologies into flight systems are discussed in section 3.6. The technologies addressed by the Transportation Technology Team in this report pursue technology needs across the broad range of civil transportation systems required to take the United States into space as we enter the 21st century.

1.4 Process Overview

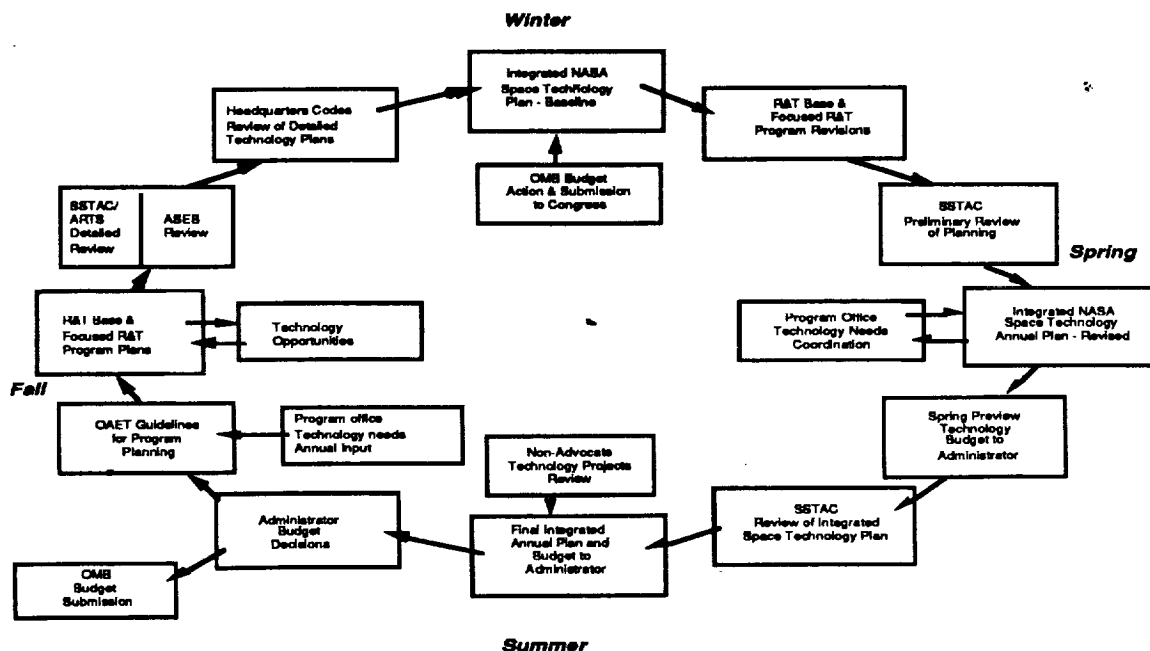
The Transportation Technology Team formed by OAET Director of Space Technology consists of senior representatives from Marshall Space Flight Center (MSFC), Johnson Space Center (JSC), Kennedy Space Center (KSC), Langley Research Center (LaRC), Lewis Research Center (LeRC), Jet Propulsion Laboratory (JPL) and the Headquarters Office of Space Flight. A space transportation specialist from an OAET Space Technology contractor, General Research Corporation (GRC), assisted in the team activities. This team is co-chaired by the NASA Headquarters Assistant Director for Space Technology (Transportation Systems) and by the MSFC Director for Research and Technology. It is anticipated that the report will be updated each year by the team and that additional volumes will be released yearly that reflect the currently funded program and the

proposed program to be funded for the following year. Figure 1-3 shows the planning flow for NASA space technology and how the requirements flow from the users to the technology plan on a yearly basis. Every February, right after the proposed budget for the next fiscal year has been sent by the President to Congress, NASA begins to assemble the budget for the following fiscal year. In the spring, this preliminary budget/plan is reviewed by the NASA field centers and the user community which previously updated and revised its technology needs/requirements, the external advisory group Space Systems and Technology Advisory Committee (SSTAC), the SSTAC Aerospace R&T Subcommittee (ARTS) and the National Research Council's Aeronautics and Space Engineering Board (ASEB). In general the review of the SSTAC and the ASEB ensures the technical quality of the various projects as well as evaluating technical progress versus objectives. During the summer, the budget/plan is further refined within NASA and sent to the Office of Management and Budget (OMB) by early September. OMB responds to the NASA proposed budget/plan by the end of November. The proposed budget is presented to Congress by the President, and the cycle repeats.

1.5 Report Organization

Chapter 2 gives an overview of the technology plan, explains the overall structure, identifies the goals and objectives and describes supporting technology programs. Chapter 3 addresses civil space transportation technology needs and delineates the specific transportation technology needs identified by OAET technology user organizations in the Agency and by the commercial transport industry in the United States. The process used to prioritize the composite technology needs list is described and this chapter also addresses Agency technology working groups which may help "bridge" technology maturation gaps between OAET and the user organizations. The Transportation Technology Plan is addressed in Chapter 4 which explains the individual program elements in a detailed fashion. This chapter discusses on-going elements and proposed technology augmentations to those elements as well as proposed new technology elements. Chapter 5 examines the implementation process including annual reviews and reports.

**Figure 1-3
Space Technology Planning Cycles**



CHAPTER 2

Transportation Technology Program Overview

2.1 Transportation Technology Program Goal and Objectives

The Transportation Technology Program is focused on the development and demonstration of technologies needed for future space transportation systems (evolutionary or new) and the general advancement of technologies required to maintain the leadership of the United States in space launch capability.

The goal is to provide vehicle systems technologies that substantially improve safety and reliability, increase system availability and provide new capabilities and improved performance while reducing life cycle costs.

To obtain this goal, a vision of the future of space launch systems is essential. The vision needs to be aggressive to ensure that technology enables future systems and to assure that technology pushes the "state-of-the-art". However, the vision is only a tool for development of specific objectives. The following vision of the future by specific transportation systems is the basis for development of the objectives of the Transportation Technology Program:

- Space Transportation System (specifically Space Shuttle Evolution):
 - The Space Shuttle will be upgraded to provide personnel transport well into the next century.
- New Manned Systems:
 - A Personnel Launch System (PLS) will be developed to provide complementary access to space during the Space Shuttle lifetime.
 - An Advanced Manned Launch System (AMLS) will be developed to provide for a long-term replacement for the Shuttle.
- Expendable Launch Vehicles (ELVs):
 - Existing ELVs will be upgraded as required to meet cargo transport requirements.
 - A National Launch System (NLS) will be developed to provide a low cost, highly reliable enhanced capability to transport cargo and the PLS.
- Upper Stages:
 - Current upper stages for ELVs and Shuttle will be upgraded to enhance performance and reliability.
 - New upper stage(s) will be developed as a part of the National Launch System.
- Heavy Lift Launch Vehicles:
 - A heavy-lift upgrade of the National Launch System (capability in the multi-

hundred ton class) will be developed for practical implementation of the Space Exploration Initiative.

- Transfer Vehicles and Landers:

- Transfer vehicles and landers necessary for the exploration of our Moon and Mars and to sustain space-based operations will be developed for implementation of the Space Exploration Initiative.

To achieve support of the specific transportation system developments currently envisioned, the Transportation Technology Program must meet strategic objectives in each of the three transportation technology areas (Earth-to-Orbit Transportation, Space Transportation, and Technology Flight Experiments). These Strategic Objectives are as follows:

- Earth-to-Orbit Transportation

- Enhance Space Shuttle safety margins and on-time performance by improving main engine components, avionics and other selected vehicle systems.
 - Develop technologies for a new manned system, the Personnel Launch System, that will serve as a near-term complement to the Space Shuttle for astronaut access to space.
 - Provide advanced technologies for a new manned system, the Advanced Manned Launch System, that will become the post-Shuttle generation piloted space transport with rapid turnaround and low operational costs.
 - Provide technologies which support development of robust, low-cost heavy-lift launch vehicles.
 - Develop and transfer low-cost technology to support commercial expendable launch vehicles.

- Space Transportation

- Develop high leverage technologies to enhance current performance of upper stages and to enable new approaches for higher Earth orbit missions.
 - Develop selected technologies to enable low-cost, high-performance, and reliable cargo and personnel transport in space for Lunar and Mars applications.

- Transportation Technology Flight Experiments

- Demonstrate Earth-to-orbit and space transportation technologies and collect critical flight research data through the implementation of in-space technology flight experiments that support all vehicle systems.

2.2 Transportation Technology Program Summary

The Transportation Technology Program includes technologies that enable expan-

sion of space transportation systems capabilities for future ambitious missions, including full studies of the Earth and its environment, automated missions to fully explore the Solar System and manned exploration of the Moon and Mars. It includes technologies that allow for evolutionary improvements in current transportation systems as well as technologies that provide the foundation for the development of major new transportation systems as needed.

The OAET Transportation Technology Program described in this document is presented in terms of a Work Breakdown Structure (WBS) which is the system for categorizing and describing NASA research in a particular field. A key purpose of this report is to map civil technology needs to OAET activities, as organized by the WBS. In particular, chapters 3 and 4 of this report describe how the OAET research program meets the needs of the user communities served by OAET.

The WBS used by OAET for transportation-related technology research, as previously mentioned, is segmented into the three technology areas of:

- Earth-to-Orbit Transportation,
- Space Transportation, and
- Technology Flight Experiments.

Earth-to-orbit (ETO) transportation is necessary to provide access to low-Earth orbit (LEO), and space transportation provides access to and from everything beyond LEO. Only surface transportation is programmatically omitted from these considerations. Figure 2-1 depicts, in a simplified fashion, the functions falling within these two technology areas. The sub-orbital STV system applies to the Moon as well as to Mars and includes ascent/descent systems. The third area, technology flight experiments, is a rather broad category consisting of efforts to develop, through space experimentation, information not available from ground-based experimentation, and, in some cases, to provide a technology validation which could not pragmatically be achieved otherwise.

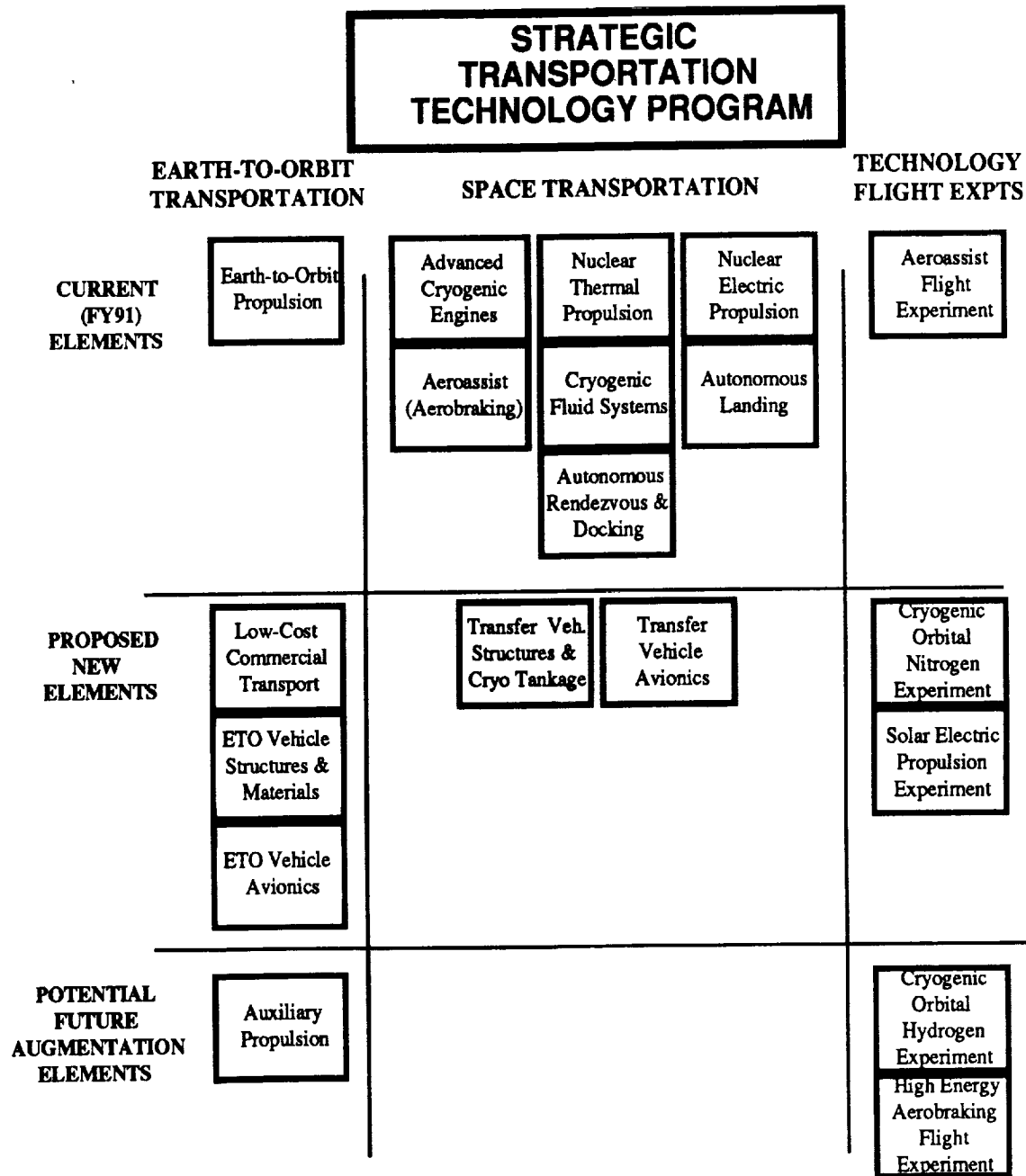
Research within each of these areas is organized by program element with each program element further divided into sub-elements. The higher level WBS for the transportation technology program is shown in Figure 2-2. Chapter 3 provides a discussion of the ranking of the technology areas and of the technology elements within each area.

These elements are geared toward currently defined needs, but also reflect generally useful areas that will support a wide range of options. The proposed technology program is both focused, to meet existing definitions of mission requirements, and flexible, to ensure that evolving mission requirements can be accommodated. From the WBS it can be seen that the high priority transportation needs include some of the most basic of transportation functions including propulsion, cryogenic fluid systems, avionics, structures and materials, and provisions for aerobraking. It should be noted that companion technology efforts concentrating on streamlining and improving ground and flight operations associated with the transportation vehicles are covered in the Operations Technology Thrust.

FUNCTIONS FALLING WITHIN EARTH-TO-ORBIT & SPACE TRANSPORTATION



Figure 2-2
STRATEGIC TRANSPORTATION TECHNOLOGY PROGRAM
WORK BREAKDOWN STRUCTURE



2.2.1 ETO Transportation Technology Area

Priority technologies in the Earth-to-Orbit Transportation area are concentrated in propulsion, structures & materials and avionics elements. Because we have more experience to date in the basics of ETO transportation, a larger share of these technology efforts can be directed toward more durable systems which are less vulnerable to failures and toward reductions in cost of hardware and operations support. Many of these technologies will have direct support for commercial ELVs; however, an entire element

(Low-Cost Commercial Transport) is devoted to specific technology efforts addressing the unique needs of the commercial space transportation industry. This includes technology work in low-cost propulsion systems, low-cost structures, materials and manufacturing methods, and low-cost avionics.

2.2.2 Space Transportation Technology Area

Some of the technology advances in the Space Transportation category are necessary to extend our mission capabilities beyond our experience to date, and therefore includes work on advanced forms of propulsion and other systems for long-duration, manned exploration missions into space. Such missions entail extended exposure to an environment involving temperature extremes, vacuum, atomic oxygen interaction, increased radiation levels and various other factors that will affect space transportation systems with critical requirements for reliability, re-usability, long storage times, and ease of operations. These propulsion forms include advanced cryogenic engines and aeroassist as well as nuclear thermal and nuclear electric. It seems clear that cryogenic propellants will be needed in some form for these long-duration missions, and technology advances are needed to insure practical storage and in-flight management of these super-cold propellants. Structures activities will contend with the long duration exposure of materials to the harsh environment of space. It appears that "aero-assist" or "aerobraking" can be used to advantage in some cases, either at a target planet or upon return to Earth, to reduce propulsion demands for the mission. Technology advances and demonstrations are required to prove out some of the basics for this new operating mode. Overlaid over these efforts to expand our operating capabilities will be a primary emphasis toward enhancing safety / reliability. Falling into this category are elements in avionics, autonomous landing and autonomous rendezvous & docking. Efforts in conjunction with ETO Transportation technologies will be developed and applied to improve operability, to reduce costs for hardware manufacturing, to improve reliability and reduce costs of software, and to reduce costs for support and operation in the space environment.

2.2.3 Technology Flight Experiments

As noted earlier, the Technology Flight Experiments category is included for cases where the technologies cannot be adequately developed and demonstrated via ground testing alone. One flight experiment in this category has been initiated and is currently under development; the Aeroassist Flight Experiment or "AFE" will return into the upper regions of the Earth's atmosphere after being launched from a Space Shuttle, to simulate return of a spaceship from a higher energy orbit, or return from a Lunar exploration mission. Later flight experiments will be needed to explore return at the higher speeds associated with Mars exploration missions (the High Energy Aerobraking Flight Experiment or "HEAFE"). The Cryogenic Orbital Nitrogen Experiment (CONE) will be the first of several flight experiments required to develop and demonstrate capabilities to store and effectively manage cryogenic fuels in zero / low gravity conditions in space. Later, a flight experiment will be considered that uses liquid hydrogen (the Cryogenic Orbital Hydrogen Experiment or "COHE"). The Solar Electric Propulsion Experiment will pave the way for use of high-performance electric propulsion in solar system exploration with automated spacecraft, and possibly open an avenue for its later use in manned exploration missions.

2.3 Other Supporting Technology Programs

As mentioned previously, the Integrated Technology Plan (ITP) consists of five

focused areas plus an R&T base research area. The Transportation thrust, as one of the five focused activities, receives direct benefit from the Operations thrust and the R & T Base program also contributes significantly to enhancing the Transportation program. The contents of these two supporting thrusts is discussed briefly here. More detail will be presented in the overall Integrated Technology Plan.

The objective of the Operations Technology Program is to develop and demonstrate technologies needed to reduce the cost of NASA operations, improve their safety and reliability, and enable new, more complex capabilities for robust, flexible support systems. At least three of the major areas of activity in this thrust will produce advances that pertain to the Transportation thrust, including:

Automation and Robotics - the development of technologies which will enable increasing levels of automation in all areas of ground and space operations. Artificial intelligence technologies will address improved mission operations, data analysis techniques, fault detection and isolation, and autonomous control. Telerobotics technologies will be applied to automating ground preparation and launch processing functions.

Infrastructure operations and crew training - the handling, processing and testing of vehicles, spacecraft, and their payloads both on the ground, in preparation for launch, and the control, maintenance and oversight of vehicles, spacecraft and their payloads during missions.

In-space operations - construction, servicing, maintenance, and use of the space infrastructure in the space environment.

The objective of the Research and Technology Base Program, as previously described, is to develop technologies and capabilities not yet perceived as critical by the user community. The principal elements of this program supporting the transportation thrust are the aerothermodynamics, propulsion, materials & structures, advanced controls and systems analysis elements. The Aerothermodynamics program is intended to characterize the fluid dynamic and thermodynamic phenomena that govern atmospheric flight of aerospace vehicles. Advances in aerodynamics and aerothermodynamics prediction capabilities are essential to the design process for a new generation of space vehicles demonstrating increased performance and reduced design margins. In order to satisfy these objectives, activities in this the Aerothermodynamics element include:

Computational tool development - detailed and approximate engineering flow field analysis, integrated fluid-thermal-structural analysis, and computational chemistry tools for calculating high temperature fluid properties,

Experimental research and computational validation - development of experimental data bases from both ground-based facilities and flight data analysis to provide understanding of physical phenomena and to validate tools,

Facilities research and development - upgrade of existing facilities, development of improved instrumentation and test techniques, and facility concept studies to address the gaps in existing flow simulation facilities,

Configuration assessment - application of the analytical and experimental capabilities just described to the synthesis, evaluation, and optimization of future space transportation systems.

The R&T Base propulsion element focuses on extending our knowledge and understanding of fundamental rocket engine chemical and physical processes which will enhance future component designs and to predict component performance and life more accurately.

The propulsion element includes:

Combustion and turbomachinery - increased understanding of rocket engine combustion stability and turbomachinery internal fluid and dynamic processes including predictive modeling.

Cryogenic propellants in space - fundamental understanding necessary for long-term storage, transfer and maintenance of cryogenic propellants in space.

Electric propulsion - very high performance low-thrust electric propulsion systems research which addresses technology issues and advanced concepts for electrothermal and electromagnetic propulsion for improved thruster life and vehicles.

Higher energy systems - such as fission, fusion, etc. which in the far future could provide high-thrust propulsion systems with capabilities far beyond those which are currently possible. Studies are being conducted to evaluate the potential of turning these high-energy sources into practical propulsion systems and identifying critical technology issues that need to be pursued.

The R&T Base materials & structures element focuses on extending space durability and environmental effects, lightweight structures for space systems and technology to enable the development of large space structures.

The materials & structures element includes:

Advanced materials and structural concepts - will be explored for integral cryogenic tanks and thermal protection systems including advanced metallic and composite cryogenic tank concepts and durable, woven ceramic thermal protection systems for future space vehicles.

In-space construction - methods will be developed, including ground-based robotic assembly of complex platforms and structural components. Techniques for on-orbit fabrication and joining of structural elements will be investigated.

The R&T Base advanced controls element in the information and controls program focuses on the development of analytical tools for the design of control systems for precision pointing and control of large flexible spacecraft and for avionics systems technology for advanced transportation vehicles.

The R&T Base systems analysis element for transportation systems centers on launch vehicle concept design studies to assess technologies for the next generation of manned launch vehicles and nuclear electric propulsion for cargo and piloted space transfer vehicles. Technology options to be studied address staged and single-stage-to-orbit vehicles, horizontal and vertical takeoff and landing vehicles, rocket and air breathing vehicles and combined engine concepts.

CHAPTER 3

Civil Space Transportation Technology Needs

3.1 Overview

A successful space program depends on available, reliable, and affordable (i.e. competitive) transportation for the broad range of science, exploration, environmental, commercial and national security missions. In Chapter 2, the vision of future launch systems was presented. This chapter develops subsystem requirements from that vision for each transportation system and WBS element within the three transportation technology areas (i.e. Earth-to-Orbit, Space Transportation and Technology Flight Experiments). The user subsystem requirements are presented as the input driver. Next, a unified and prioritized list of requirements is presented. Finally, activities to bridge the gap between traditional technology development and user advanced development programs are discussed.

3.2 NASA Transportation Vision

Currently identified future U.S. space missions impose launch requirements that can only be satisfied with significant advances in technology and with the development of an appropriate mix of both manned and unmanned vehicles to carry crews and payloads into Earth orbit and then beyond into the solar system.

The Space Station Freedom (SSF), planned for initial man-tended operation in 1997, will require significant launch support during buildup, and will place a continuing requirement on the Earth-to-orbit launch system to provide logistics support and eventually, system enhancements.

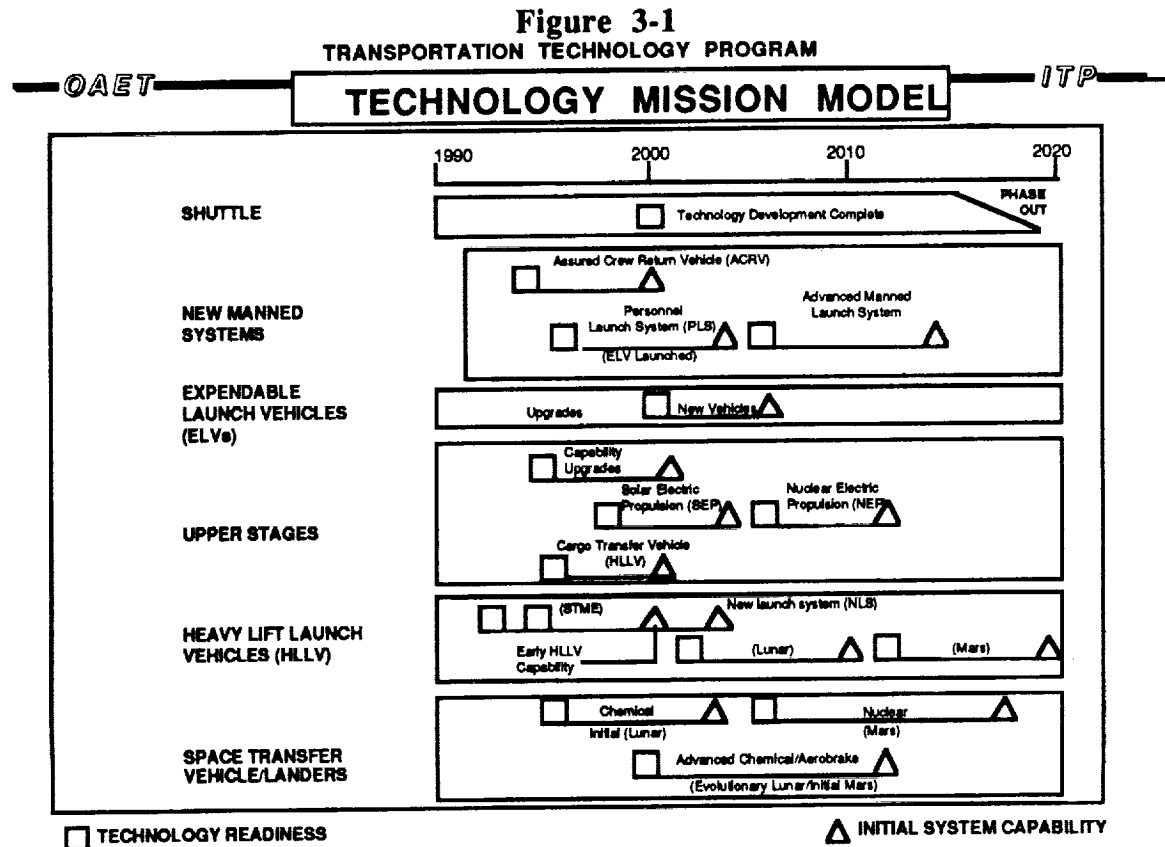
The Space Exploration Initiative (SEI), which calls both for a manned lunar base and for Mars exploration, is now being defined as a long-term NASA objective. The SEI program will require delivery to low-Earth orbit of large masses for assembly of the space transfer and lander vehicles, for propellant and tanks to fuel these vehicles and for the men and cargo they will deliver.

Regardless of how these missions are finally defined and timed, space missions and NASA's goal of assured access (including manned) to LEO, dictate a launch payload capability, frequency, and reliability that will require advances in many focused technology areas in order to provide the technology upon which new launch systems will be based. These technology developments must be achieved in a timely fashion so that launch system development schedules can be achieved in response to mission requirements.

The transportation development scenario now considered most probable is shown in Figure 3.1. Essentially, it assumes that the Space Transportation System, i.e. Space Shuttle, will continue, with some improvements, to be the prime manned carrier as we enter the 21st century. A new Personnel Launch System, intended to satisfy the need for assured manned access to space, will be developed as a manned upper stage launched by an expendable vehicle. This may well be complemented by single-stage-to-orbit concepts now being studied and, eventually, by the second generation STS, known as the Advanced Manned Launch System, which must await substantial technology development.

For small, one-way payloads, such as weather and communication satellites that do not require handling by man, expendable launch vehicles will continue to be the principal

launch system due to their unique capabilities (polar launch, cryogenic upper stages, etc.). The NLS will be developed to upgrade the cargo delivery capability of the U.S. In the near term, a heavy lift launch vehicle (HLLV) to support civil needs (cargo and PLS) will be derived from the NLS program, which will be followed in 10 to 15 years by a second-generation HLLV supporting the SEI payloads. For orbital transfer and interplanetary flight, upgrades are required in upper stage capabilities and for man and cargo to support SEI, new space transfer and lander vehicle systems must be developed. A typical upper stage scenario includes upgrades to current upper stages, a Cargo Transfer Vehicle (CTV) for use in conjunction with NLS launch vehicles, and solar/nuclear electric stage(s) for automated spacecraft missions requiring high levels of propulsion efficiency.



3.2.1 Earth-to-Orbit Launch Systems

Earth-to-orbit (ETO) launch systems include the Space Shuttle and new manned systems which may include a Personnel Launch System, Advanced Manned Launch Systems, Expendable Launch Vehicles and the National Launch System. The Space Shuttle will need to incorporate new technologies as it begins to experience technological obsolescence. The next generation of manned launch systems must satisfy mission requirements for placing payloads and people into low-Earth orbit with greater cost effectiveness than the STS, improved crew safety and increased performance margins and operational reliability.

The PLS may be derived from the Assured Crew Return Vehicle (ACRV) or it may be a new vehicle concept. It will need electromechanical actuators to move aero-surfaces and to gimbal small orbit-maneuvering rocket engines, fault-tolerant avionics enabling significant

vehicle flight autonomy, graphite-polyamide and aluminum-lithium structures for weight reduction, thermal protection systems toughened for durability to reduce ground maintenance requirements and automated checkout procedures and advanced automated systems for launch and mission control. A number of the near-term technologies needed for PLS would also benefit a near-term AMLS.

The AMLS will require an order-of-magnitude improvement in processing workload, turnaround time, vehicle life, and cost per flight. Dedicated technology initiatives underway in the United States in the National AeroSpace Plane (NASP), Single Stage To Orbit (SSTO), NLS, and other NASA focused technology programs will have major impacts on vehicle concepts designed in this decade; thus, it is useful to examine technologies for an AMLS vehicle on two distinct levels -- evolutionary and advanced.

Assuming only evolutionary technology advancements, composite and honeycomb primary structures are lightweight and able to endure significantly higher temperatures. Reusable aluminum-lithium cryogenic propellant tanks provide lighter weights and lower cost. For primary propulsion, highly reliable low-maintenance reusable engines are needed. On the subsystems level, hydraulics will be replaced with all-electric systems employing electromechanical actuators for both engine gimbal and aero-surface controls, hypergolic propellants in orbital maneuvering and reaction control systems (OMS and RCS) are replaced by nontoxic, cryogenic, hydrogen-oxygen systems and advanced avionics can help decouple the vehicle from a majority of ground-based mission control functions.

Major advances in technologies such as advanced high-temperature, high-strength lightweight materials would enable either horizontal or vertical-takeoff AMLS single-stage launch vehicles. In this category are metal matrix materials including titanium aluminides for primary structures and advanced carbon-carbon composites for the hottest parts of the wings and fuselage. Propellant tanks may be constructed from thermoplastic material. Leading edges of wings and engine ducts, inlets, and nozzles for air-breathing systems require active cooling because the heating rates are very high and shock interactions impinge on the vehicle. Advanced propulsion system options include lightweight dual-fuel or variable mixture ratio rocket engines and combined air-breathing and rocket engine systems.

The Expendable Launch Vehicle fleet is provided by industry and sold to the government for launching a wide class of payloads. In addition to serving user communities within NASA, OAET also addresses technology needs of the aerospace industrial community including the commercial space transportation industry. The commercial space transportation industry has been recognized by Congress and the President to be critical to the economic future of the U.S., and national policy dictates increasing reliance by government agencies on commercial space launch services. As directed by the Commercial Space Launch Act Amendments of 1988, NASA's OAET in conjunction with the commercial launch vehicle industry, developed a plan for the component level research and technology required to reduce the initial and recurring costs, increase reliability and improve performance of expendable launch and upper-stage space vehicle systems used for commercial service [Expendable Launch Vehicle Technology - A Report to the U.S. Senate and U.S. House of Representatives, July 1990]. Industry is primarily interested in reducing initial and recurring costs while increasing reliability and improving performance of expendable launch and upper-stage space vehicle systems used for commercial service.

National Launch System technologies needed to address design goals can be categorized into three major areas. Propulsion technology needs include: a robust, low cost engine; electromechanical actuators; and health monitoring sensors and systems. Avionics needs

include: advanced software generation; adaptive GN&C; and advanced automated systems for vehicle status monitoring and management. Structures and materials needs include light-weight and high temperature metallics for tanks and light-weight, damage-tolerant and repairable composites for non-pressurized structures.

3.2.2 Space Transportation

Technology advances are needed to expand capabilities, improve efficiencies, and reduce or limit costs for in-space transportation systems. These systems include upper stages for unmanned launch vehicles, vehicles for local-area in-space movements, interplanetary transfer vehicles, and high-performance vehicles for human exploration of the Moon and Mars.

Upper Stages technology developments in highly efficient cryogenic (LOX/H₂) propulsion systems are needed to upgrade performance or capabilities for continued support of Earth orbit satellite missions and solar system exploration. To extend capabilities to explore outer planets and other bodies, new levels of technologies are needed in the form of highly efficient electric propulsion systems using either nuclear or solar power sources. To enable precision maneuvering and highly reliable operations in the near vicinity of Space Station Freedom or at other space facilities where movement of large payloads and/or assembly or processing activities are to take place, automated rendezvous & docking technologies are required for the Cargo Transfer Vehicle.

Space Transfer/Excursion Vehicles for Earth orbital and interplanetary transfer are differentiated from ETO systems by their long-term exposure to the space environment. For orbital transfer stages or Lunar missions measured in days, significant economic advantages may be gained by basing systems in LEO for reuse, thus avoiding the discarding of hardware elements and reducing launch costs for replacements. However, the systems must survive for long periods on-orbit. Emphasis is established on high propulsion performance and upon propulsion-enhancing approaches such as aero-capture. Nuclear propulsion options require thorough examinations for reducing Mars mission transit times and associated crew exposures, as well as potential for reductions in space vehicle masses and ETO launch requirements. Technology advances are needed to learn and to demonstrate methods for effectively using cryogenic propellants over long periods in space. Space basing will present unique technology challenges that must be met to assure re-usability of systems while minimizing maintenance operations. Technology advances are needed in the avionics systems that must serve as the brains and nerve systems for these space ships. New levels of self-testing and health management are needed to ensure continued reliability of operations and to minimize requirements for crew attention and involvement. The mass and dimensions of assembled and fueled vehicles will normally exceed our single-launch delivery capabilities, and will require some levels of in-space vehicle docking/ assembly, check-out and processing.

3.2.3 Technology Flight Experiments

Many of the technology proposals identified in this transportation plan will require testing in the relevant space environment to provide the confidence level necessary before the technology can be inserted into a vehicle development program. These flight experiments, in conjunction with ground testbeds, serve to bridge the gap between the technology research and the flight programs, and, as such, demonstrate performance and mitigate programmatic risk.

The Space Shuttle Orbiter has served as a flying national research test bed laboratory to

demonstrate principles including payload handling, retrieval, servicing, hypergolic propellant transfer, space assembly, Orbiter Experiments, active thermal control. However, flight prototyping can be expensive, depending on the scale of projects and complexity of operations and vehicle integration. Therefore, flight experiments should be considered only where there are large unknowns that can be adequately simulated only in the real space environment (where ground test facilities and analysis methods are inadequate in simulating the proper environment throughout the full operational envelope).

The Aeroassist Flight Experiment is an example of a large flight program at the "enabling" end of the spectrum. The analytical computational fluid dynamic (CFD) codes can be validated only with empirical data obtained in a space relevant environment at hypervelocity speeds in the exoatmosphere. The cryogenic fluid transfer experiments also fall in this category due to the unique zero-g behavior of these fluids, e.g., surface liquid/gas mass centroid characteristics, pressure control/thermal management techniques, and two-phase flow potential (transfer high quality/density fluid vs gas ullage). Other potential technology flight experiments are focused on cryogenics, autonomous rendezvous/docking, solar electric propulsion, autonomous landing, etc. in high-risk mitigation and leverage areas.

3.3 Summary of User Technology Needs

In the spring and summer of 1991, the NASA "user" codes (OSF, OSO, OSSA, SEI in OAET) submitted their technology needs for the future. These needs were prioritized by the user codes prior to submission to OAET. It is expected that the needs list will be updated annually by each user code.

3.3.1 Office of Space Flight Technology Requirements

The technology requirements submitted by OSF in April 1991 were divided into two categories: NASA Program Unique Technology Requirements (Shuttle, Space Station Freedom, and Flight Systems) and Industry Driven Technologies. The Flight Systems Directorate has the most diverse technology requirements within OSF and carries the responsibility for identifying, exploiting and incorporating new advanced technologies into concept definition, pre-Phase A and Phase A & B study activities. It was felt by OSF that NASA should allow industry to continue pursue the industry driven activities independently as far and as fast as possibly before firmly establishing a technology requirement. Thus, OAET should primarily focus on the NASA Program Unique Technology Requirements while continuing to follow industrial activities in order to be a smart buyer.

Based on the OSF strategic plan, an alternative transportation system to the Space Shuttle is expected to start around the year 2005. According to the memo¹ from the Associate Administrator for Space Flight accompanying the technology requirements document (Reference: OSF, April 1991), this will provide an opportunity to incorporate new technology on a broad scale into a next generation vehicle. The memo made the point that the technology and advanced development tasks/programs are so intertwined that it is difficult in some cases to separate the technology tasks from the development tasks and thus will require communication between OSF and OAET personnel.

Because OSF currently lacks an assigned role and mission for SEI, requirements for SEI technologies were not included in the assessment. OSF employed a grass roots and top down assessment approach involving OSF Center personnel and OSF Program Directors to identify technology needs. OSF plans to update these technology requirements on an annual basis.

The required technologies are shown in Figure 3-2 in decreasing order of priority with transportation related technologies highlighted in bold type. The OSF point-of-contact for the identification of technology requirements is Mr. Chester Vaughan/Code MZ at Headquarters.

Figure 3-2

OSF Technology Needs	
Program Unique Technologies	
1	Vehicle Health Management
2	Advanced Turbomachinery Components & Models
3	Combustion Devices
4	<i>Advanced Heat Rejection Devices</i>
5	<i>Water Recovery & Management</i>
6	<i>High Efficiency Space Power Systems</i>
7	<i>Advanced Extravehicular Mobility Unit Technology</i>
8	Electromechanical Control Systems
9	<i>Crew Training Systems</i>
10	Characterization of Al-Li Alloys
11	Cryogenic Storage Handling & Supply
12	Thermal Protection Systems for High-Temp. Applications
13	<i>Robotic Technology</i>
14	<i>Orbital Debris Protection</i>
15	Guidance, Navigation & Control
16	Advanced Avionics Architectures
Industry Driven Technologies	
1	Signal Transmission & Reception
2	Advanced Avionics Software
3	Video Technologies
4	Environmentally Safe Cleaning Solvents, Refrigerants & Foams
5	Non-Destructive Evaluation

- Vehicle Health Management (VHM) - Develop flight and ground avionics systems that enable automated/autonomous vehicle checkout and monitoring to reduce launch processing and mission operations costs. Develop flight systems that allow orbital vehicles to support extended duration missions, possibly involving protracted periods of dormancy. Increase vehicle/system robustness and reliability while reducing requirements for ground processing and logistics support. VHM will support avionics/electronics, mechanical, structural, fluid and propulsion systems. Applications include Space Shuttle, Space Station Freedom, CTV, STV, ACRV, PLS, HLLV, AMLS, NLS, and NASP.
- Advanced Turbomachinery Components and Models - Define, develop and demonstrate materials, manufacturing processes and design methodologies for advanced turbomachinery including bearing, impellers, inducers, blades, disks, seals and instrumentation. Develop advanced models to accurately predict performance, loads, and component life margins. Validate codes, methodologies, processes and design practices for low cost, reliable components through prototype fabrication and demonstration. Applications include NLS/STME, SSME and ELV.

- Combustion Devices - Develop fabrication methods for engine thrust chambers and related components for more robust, larger-margin designs and low cost fabrication. Develop design codes, methodologies and validated design practices for low-cost engines and component specifications. Application to prototypes and to component demonstration and verification. Applications include NLS/STME, SSME and ELV.
- Electromechanical Control Systems/Electrical Actuation - Develop and qualify advanced architecture electromechanical control systems (EMCS) to replace current hydraulic powered systems with improved performance in power, stability margins, rate response, time/frequency response and weight/size compatibility. Applications are NLS, Space Shuttle and STME.
- Characterization of Al-Li Alloys - Complete the characterization of selected Al-Li alloys and document the process, joining and welded applications to handbook levels for designers' use. Design, fabricate and demonstrate through the use of test large-scale component manufacturing, incorporating NDE process control. Applications include STS External Tank, Upper Stage Tankage, NLS Vehicle Structure and Tankage, and STS Primary Structure.
- Cryogenic Supply, Storage and Handling - Establish a technology base and preferred practices incorporating design codes for subcritical cryogenic supply, storage and handling under zero-g conditions including the critical areas of thermal control, pressure control, liquid supply, fluid handling, fluid transfer and cryogenic leak-proof coupling/joints. Applications include STV, SEI (LTV, LEV, MTV, MEV), SSF node, In-space refueling facilities and supporting operations.
- Thermal Protection Systems (TPS) for High Temperature Applications - Develop and demonstrate durable thermal protection systems for high temperature vehicle applications: reusable, flexible TPS materials with heating rates of 35-60 BTU/ft²-sec; reusable long-life, rigid materials with heating rates of 50-75 BTU/ft²-sec; advanced carbon-carbon TPS characterization and fabrication methods including coatings and fasteners; and all systems requiring less operational support having increased impact damage resistance, permitting large section fabrication and fail-safe operation. Applications include NLS, PLS, STV, CTV and AMLS.
- Guidance, Navigation and Control (GN&C) - Identify, develop and demonstrate GN&C architectures, sensors and algorithms for space systems including: autonomous GN&C techniques, rendezvous, entry, landing, ascent and on-orbit operations. Define functional requirements and design guidelines that emphasize: lower acquisition costs and development time; better maintainability; allowance for growth and adaptability; support for vehicle health management systems; and core application to a number of space vehicles. Applications are STS, SSF, PLS/ACRV, NLV and AMLS.
- Advanced Avionics Architectures - Assess and develop common "open" space avionics architectures for low-cost launch vehicles, future space flight vehicles and surface systems. Define design guidelines and functional requirements that emphasize: modular, scalable architectures with common interfaces; autonomous real-time operations; automated FDIR and dormancy support; simplified flight critical core avionics; vehicle health management and redundancy management strategies; and high reliability and safety. Incorporate

design and verification tools that will yield major improvements in operability, logistics and affordability. Applications are advanced Space Shuttle, SSF, PLS, ACRV, CTV, STV, LTV, MTV, MEV, Surface Systems, NLS and NASP.

3.3.2 Office of Space Exploration (OSE) Technology Needs and Priorities

Space Exploration Initiative (SEI) focused research and technology requirements were divided into three major categories: Priority 1 - Enabling for all or most SEI architectures; Priority 2 - High leverage for all or most SEI architectures and enabling for a specific SEI architecture; Priority 3 - High leverage for a specific SEI architecture.

This prioritization does not take into account the recently released Synthesis Group report but is based upon three previous assessments of technology needs: pre-90 Day Study work, the 90-Day Study (November 1989) and post-90-Day Study Work. An update of these requirements which will reflect the Synthesis Group report findings will be made by the end of 1991. There is no implied prioritization within a priority category. Technologies highlighted in bold print indicate transportation-related technologies.

The SEI requires the development of an Earth-to-orbit capability to augment that provided by the Space Shuttle and existing ELVs. Requirements for this capability will be defined based on a range of reference missions to support both lunar emplacement strategies and Mars mission strategies. Technology need dates are divided into three time increments of five years each (near-term, mid-term and far-term). For planning purposes, the following should be assumed:

Earth-to-Orbit Capability

- Launch capability for lunar missions in the 130-150 metric tonne (mt) class (net) accommodating an 8-10 meter diameter payload.
- Assume four ETO (130-150 mt) launches per year to support initial lunar missions.
- Initial launch capability for Mars missions shall be in the 225-275 mt class (net) accommodating a 17-20 meter diameter payload.
- Assume four ETO (225-275 mt) launches per 26 month period to support initial Mars missions.
- New launch vehicles shall preserve the option of eventually being man-rated.

Space Transportation Vehicles

- Capability to transport crews and cargo from Earth orbit to the Moon and Mars.
- Capability to evolve to reusable, space-based transportation vehicles when and where beneficial.
- Options to use advanced propulsion choices that make trip times to Mars shorter than 500-1000 day class missions.
- Ensure that radioactive materials are prevented from entering Earth's biosphere.

Priority 1

Near-Term Application: Initial Lunar Outpost

Mid-Term Applications: Upgraded Lunar Output, Initial Mars Missions

Far-Term Applications: Initial Mars Missions, Mars Outpost

- Cryo Fluid Management, Storage & Transfer [vehicle cryogenic fluid storage technology, cryo fluid management for vehicle propulsion feed supply to engines]
- Aerobraking [low energy at <12 Km/s entry speeds, high energy at >12 Km/s entry speeds]
- Nuclear Thermal Propulsion [reactor design, fuel development, shielding and control systems]

Priority 2

Near-Term Application: Initial Lunar Outpost

Mid-Term Application: Upgraded Lunar Outpost

Far-Term Application: Initial Mars Missions, Mars Outpost

- Autonomous Rendezvous and Docking [includes unmanned docking and verification of successful mating]
- Cryo Space Engines [includes space transfer vehicles and landers, restart capability, ability to throttle over a wide range, and ease of maintainability are included]

Priority 3

Near-Term Application: Initial Lunar Output

Mid-Term Application: Upgraded Lunar Outpost

Far-Term Application: Initial Mars Missions, Mars Outpost

- Autonomous Landing [GN&C, transition from aero to propulsion and landing at a fixed spot, nav aids, hazard avoidance]
- Electric Propulsion [nuclear and solar propulsion thruster development]

The point of contact for the space exploration technology requirements is William Smith/Code RZ at NASA Headquarters.

3.3.3 Office of Space Science Applications Technology Needs

Major OSSA programs are Life Sciences, Earth Science, Solar System, Microgravity, Space Physics and Astrophysics. All OSSA divisions identified mission sets and relevant technology priorities. This listing does not include inputs from the strategic planning summer workshop conducted in July and August by OSSA and the Space Science and Applications Advisory Committee (SSAAC). Refinements to the priorities listing below will be made in the next revision of this report. The principal point of contact for this activity is Joe Alexander, Assistant Administrator for Science and Applications (Code S at NASA Headquarters). The technology priorities shown in Figure 3-3 are all far-term needs.

Figure 3-3
OSSA Technology Priorities

Highest Priority:
<ul style="list-style-type: none">• 50-100 kW Ion Propulsion (NEP)
2nd-Highest Priority Needs:
<ul style="list-style-type: none">• Mini Ascent Vehicle/Lander Deceleration
3rd-Highest Priority:
<ul style="list-style-type: none">• Auto-Rendezvous• Auto-Sample Transfer• Auto-Landing

3.3.4 Office of Space Operations Technology Needs and Priorities

In the near term, the additional technology needed by OSO will be a refinement and extension of existing technology rather than radically new technology. For the longer term, OSO's technology requirements will mature as specific technologies needed by future space missions emerge. OSO anticipates that inputs, particularly from OSF, OSSA and the Office of Space Exploration will provide this information. OSO's longest-range technology needs are emerging from its participation in agency-wide Lunar and Mars exploration studies. Major OSO programs include the Deep Space Network (DSN), the Space Network, Mission Operations Centers, and advanced geostationary communications satellites. Points of contact for space operations technology requirements are Hugh Fosque/Code OP at NASA Headquarters (general operations) and Albert Miller/Code O at NASA Headquarters (SEI operations).

Technology needs include:

- Advanced Navigation Techniques - new planetary navigation techniques during cruise, approach and in-orbit navigation for robotic missions [near-term]. Require new planetary navigation techniques during cruise, approach and in-orbit navigation for robotic and human missions [mid-term].

3.3.5 Commercial Requirements

Overall technology needs exist for expendable launch vehicles communications satellites, Earth observation satellites, and space manufacturing. These needs are preliminary and were extracted from Aerospace Industries Association (AIA), National Research Council (NRC), and DOT Commercial Space Transportation Advisory Committee (COMSTAC) sources. Continuing dialogues with the space launch industrial community will be employed to more accurately determine specific commercial ELV technology requirements. Current plans call for a NASA Research Announcement (NRA) calling for cooperative areas of research to be funded. Response to the NRA will be a determining sign of the amount of interest in cost sharing in order to improve current ELV technologies while providing the technology foundation for the next generation of ELVs.

Commercial ELV technology needs are very similar to government launch vehicle technology needs. However, because the cost and risk of incorporating unproven technology may be prohibitive for commercial entities, additional technology development and even technology validation may be required for NASA research to be useful to commercial firms.

The technology requirements defined here generally reflect the needs of commercial firms manufacturing and marketing large ELV systems with long histories of use. There are new commercial space transportation firms whose needs require additional analysis. These firms are using innovative technologies, and are investigating new capabilities such as re-entry and retrieval of payloads and the development of small ELVs. NASA is continuing to evaluate the requirements of the commercial space transportation industry, with particular attention to the requirements resulting from the development of small payloads and ELVs and resulting operational considerations (i.e., re-entry and retrieval).

NASA, the Department of Transportation (which regulates the commercial space transportation industry), the Department of Commerce, advisory groups to these agencies, and various industrial groups have in recent years conducted studies to identify the technology needs of the commercial space transportation industry.

The overall needs of the commercial space transportation industry are to reduce cost and to improve performance (i.e. lift capacity), reliability, and resiliency/operability. Cost reduction is the primary goal. ELV costs are evenly distributed among propulsion, materials & structures, and avionics & operations, the three technology areas that account for the major percentage of ELV costs.

Propulsion technology requirements focus on the need for low-cost propulsion systems for both lower and upper stages. Industry decisions about future propulsion systems and subsequent industry development activities will require research into launch stage propulsion systems (based on NASA findings, in order of preference expressed by industry representatives) including LOX/Hydrogen, LOX/Hydrocarbon, Solid, and Low-Pressure Booster systems. For upper stage propulsion systems, industry representatives have identified interest in LOX/Hydrogen, Storable Liquid, Solid, and Hybrid systems. A COMSTAC assessment identified specific high priority projects in the propulsion and fluid

systems area. These were:

- low cost liquid booster engines - hydrogen/oxygen
- low cost liquid booster engines - hydrocarbon (evolutionary)
- hybrid propulsion strap-on boosters with transition to high regression rate non-oxidized fuel)
- advanced low cost LOX/liquid hydrogen upper stage engine (30,000-50,000 lb of thrust)
- advanced low-cost LOX/liquid hydrogen upper stage engine (100,000-200,000 lb of thrust)
- leak-free tubing and ducts
- low-cost pressure fed engine & turbopump technology
- clean burning solid motor technology
- improved LOX/RP-1 and storable derivative engine components.

Materials and structures technology requirements, based on NASA findings, include both near term, high priority needs including low-cost cryotanks (including aluminum-lithium metallic tanks and filament-wound composite structures), low cost composite dry structures, advanced thermal protection systems, and low-cost manufacturing and processing methods. Longer-term requirements include development of new materials, advanced aluminum-lithium alloys and thermoplastic composites for cryotanks, interstages, and shrouds. The DOT COMSTAC assessment identified specific high priority projects in the advanced structures area. These were:

- low-cost aluminum-lithium alloy tanks and structure (design, materials, and fabrication), and
- low-cost composite structure.

Avionics and operations technology requirements focus on the development of autonomous, adaptable, and fault-tolerant avionics systems to increase reliability, safety, and flexibility, and to reduce cost. Research areas identified by NASA, with industry input, include guidance and control for upper winds loading relief, next-generation fault tolerance avionics, photonic technology for far-term flight crucial systems, integrated electromechanical actuators, power, and controls, and automated ground and launch operations. In addition, industry representatives have stressed that flight validation to reduce the risk of new technology application is a particularly important consideration for ELV avionics. A DOT COMSTAC assessment identified specific high priority projects in the avionics area. These were:

- low-cost multi-path fault tolerant redundant avionics,
- adaptive guidance, navigation, and control systems,
- electromechanical actuators, and
- low-cost GPS-based guidance.

COMSTAC also identified specific high priority projects in the areas of production and launch operations. These were:

- adaptive computer controlled welding/automatic inspection,
- computer integrated manufacturing (CIM),
- automated ground and airborne operations with automatic pre- (and post-) flight data and analysis, integrated health monitoring, and intelligent operation "expert" systems, and
- standardized payload interfaces.

3.4 Prioritization Process

A key element of the development of the Integrated Technology Plan is a consistently applied ranking and prioritization process. The prioritization and ranking process used the judgment of Transportation Technology Team members, based on an understanding of civil space mission plans and resulting mission needs. The Team was supplied with data on NASA long-range civil space mission plans.

The Transportation Team members ranked the three technology areas, and program elements within each technology area. The criteria used in ranking program elements and program areas are listed below. The first set of criteria listed guided individual Team members in preparing their ranking of program elements and program areas. The latter group of listed criteria were used by the Transportation Team co-chairmen and NASA OAET management in refining the ranking as needed to reflect institutional and external factors. The results of the ranking process then served as a guide (not an absolute measure) for the allocation of resources to achieve the considered budget levels.

The criteria used by the Transportation Team members for ranking the program elements within each technology area included the following considerations:

- Meet common high-priority user needs
- Meet high-priority user needs
- Continue initiated technology programs unless needs cease
- Provide leverage (cost/benefit, initial, DDT&E, total)
- Provide reasonable risk (per potential)
- Provide commercial potential
- Entail multi-agency participation
- Entail good "program initiation" probability (likely resources available, interest, etc.)

Management overlay factors included:

- Provide/maintain institutional stability
- Provide proper program size balance
- Provide "bridging" ease
- Provide potential for social spinoffs
- Follow Augustine Committee Report recommendations

Utilizing these criteria, the transportation technology areas were rated in order of increasing significance: Technology Flight Experiments (3rd priority), Space Transportation (2nd

priority) and ETO Transportation (top priority). Overall rankings by the various technology thrust teams with management overlay criteria factored in by OAET Space R&T management of user technology requirements from all five technology thrusts are shown in Figure 3-4.

Figure 3-4
INTEGRATED TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM
Strategic Plan/User Key Requirements Focused Thrusts Categorization

OAET									
Space Science Observations Technology	Submillimeter Sensing	Direct Detectors	Active Microwave Sensing	Sample Acq., Analysis & Preservation	Passive Microwave Sensing	—	Optoelectronics Sensing & Processing	Probes and Penetrators	—
	Cooler and Cryogenics	Sensor Electronics Microprecision CSI	Laser Sensing Telescope Optical Systems	Data Archiving and Retrieval	Data Visualization	—	Precision Instrument Pointing	Sensor Optical Systems	—
Planetary Surface Exploration Technology	Radiation Protection	Regenerative Life Support (Phys-Chem.)	Space Nuclear (SP-100)	High Capacity Power	Planetary Rovers	Surface Habitats and Construction	Exploration Human Factors	—	Artificial Gravity
	—	—	Extravehicular Activity Systems	Surface Solar Power and Thermal Mgt.	In Situ Resource Utilization	Laser Electric Power Beaming	Medical Support Systems	—	—
Transportation Technology	ETO Propulsion	Nuclear Thermal Prop. Aerospace Flight Expt	Aerospace/Aerobraking	Transfer Vehicle Avionics	ETO Vehicle Avionics	ETO Vehicle Structures & Materials	Autonomous Rendezvous & Docking	CONE SBPS	Auxiliary Propulsion
	Cryogenic Fluid Systems	Advanced Cryo. Engines	Low-Cost Commercial ETO XPort	Nuclear Electric Propulsion	CONE	—	Autonomous Landing	TV Structures and Cryo Tankage	HEAB
Space Platforms Technology	Platform Structures & Dynamics	Platform Power and Thermal Mgt.	Zero-G Life Support	Platform Materials & Environ. Effects	Station-Keeping Propulsion	—	Spacecraft On-Board Propulsion	Earth-Orbiting Platform Controls	Advanced Refrigerator Systems
	—	—	Zero-G Advanced EMU	Platform NDE-NDI	Deep-Space Power and Thermal	—	Spacecraft GN&C	Debris Mapping Experiment	—
Operations Technology	Space Data Systems	High-Rate Comm.	Artificial Intelligence	Ground Data Systems	Optical Comm Flight Expt	Flight Control and Operations	Space Assembly & Construction	Space Processing & Servicing	Photonics Data Systems
	—	CommSat Communications	TeleRobotics	Operator Syst./Training	Rt. TeleRobotic Services/DTF-1 Navigation & Guidance	CommSat Communications Flight Expts	—	Ground Test and Processing	—
<div style="display: flex; justify-content: space-around; align-items: center;"> <div style="text-align: center;"> HIGHEST PRIORITY 000 </div> <div style="text-align: center;"> 2nd-HIGHEST PRIORITY 00 </div> <div style="text-align: center;"> 3rd-HIGHEST PRIORITY 0 </div> </div>									

AUGUST 7, 1991
JCM-6500m

3.5 Summary of Technology Needs to Be Addressed By Transportation Technology Program

The basic principle of the Integrated Technology Planning Activity is that the Space Research and Technology Program should be driven by mission needs. The Transportation Technology Program addresses missions through the development of the technologies needed for civil space transportation systems now and in the future. It will address user needs identified by the Office of Space Flight, the Office of Space Science and Applications, the Space Exploration Initiative, and the commercial space sector of industry. These technology needs are identified in Figure 3-5 for all sectors. The Office of Space Flight is the current largest user of OAET technologies.

In propulsion systems, these technology needs include automated health management, advanced turbomachinery components and models, combustor devices, electromechanical actuators, nuclear thermal propulsion, nuclear electric propulsion, aerobraking, advanced cryogenic space engines, solar electric propulsion, low-cost re-useable booster engines, hybrid and pressure-fed boosters, non-destructive evaluation, leak-free tubes and fittings, automated pre- and post-flight data analysis, computer integrated design, manufacturing and test and an advanced liquid oxygen/liquid hydrogen upper stage engine.

Vehicle structures and materials technology needs include characterization of aluminum-lithium alloys, cryogenic fluid management, storage and transfer, handling & storage, low-cost aluminum-lithium alloy structures and cryogenic tanks, low-cost composite and metal matrix structures and tanks, advanced manufacturing, processes and welding, thermal protection systems for high temperature applications and computer integrated design, manufacturing and test.

Avionics technology needs embrace advanced adaptive, fault-tolerant guidance, navigation and control, GPS-based guidance, advanced avionics architectures and software, non-destructive evaluation, autonomous rendezvous and docking, autonomous sample transfer, autonomous landing, and electromechanical actuators for power management and control.

Figure 3-5
Relationship of Transportation Technology Program to Mission Needs
TRANSPORTATION TECHNOLOGY PROGRAM ACCOMMODATION OF USER NEEDS

<div>PROGRAM AREAS</div> <div>TECH. USERS</div>	ETO TRANSPORTATION	SPACE TRANSPORTATION	TECHNOLOGY FLIGHT EXPERIMENTS	MAJOR USER NEEDS ADDRESSED
OFFICE OF SPACE FLIGHT	<div>ETO PROPULSION</div> <div>ETO VEHICLE SAM</div> <div>ETO VEHICLE AVIONICS</div>	<div>ADV CRYO ENGINES</div> <div>TRANSFER VEH AVION</div> <div>TRANSFER VEH STRUC</div> <div>CRYO FLUID SYSTEMS</div>	<div>CONE FLT EXPT</div> <div>COHE FLT EXPT</div>	Vehicle Health Management Advanced Turbomachinery Components & Models Combustion Devices Electromechanical Control Systems Characterization of Al-Li Alloys Cryogenic Storage/Handling/Supply TPS for High Temperature Applications Advanced GN&C Advanced Avionics Architectures & Software Non-Destructive Evaluation (NDE)
OFFICE OF SPACE SCIENCE AND APPLICATIONS		<div>NEP</div> <div>AUTONOMOUS LANDING</div> <div>AUTON REND & DOCK</div>	<div>SEP FLIGHT EXPT.</div> <div>AEROASSIST FLT EXPT</div>	50-100 kW Electric Propulsion (NEP) Mini Ascent Vehicle/Lander Deceleration Autonomous Rendezvous Autonomous Sample Transfer Autonomous Landing
SPACE EXPLORATION INITIATIVE		<div>NTF</div> <div>NEP</div> <div>CRYO FLUID SYSTEMS</div> <div>AEROASSIST</div> <div>AUTON REND & DOCK</div> <div>AUTONOMOUS LANDING</div> <div>ADV CRYO ENGINES</div> <div>TRANSFER VEH AVION</div> <div>TRANSFER VEH STRUC</div>	<div>AEROASSIST FLT EXPT</div> <div>CONE FLT EXPT</div> <div>HI ENERGY AFE FLT</div> <div>COHE FLT EXPT</div>	Nuclear Thermal Propulsion Cryo Fluid Management, Storage, & Transfer Aerobraking Autonomous Rendezvous & Docking Advanced Cryo Space Engines Autonomous Landing Electric Propulsion (Nuclear/Solar)
COMMERCIAL SPACE SECTOR	<div>ETO PROPULSION</div> <div>ETO VEHICLE SAM</div> <div>ETO VEHICLE AVIONICS</div> <div>LOW-COST COMM. TRANSPORT</div>	<div>ADV. CRYO ENGINES</div> <div>NUCLEAR ELECTRIC PROPULSION</div> <div>TRANSFER VEH AVION</div> <div>TRANS. VEH. STRUCTURES</div> <div>CRYO FLUID SYSTEMS</div>	<div>SEP FLIGHT EXPT.</div>	Low-cost Booster Engine/Rt use Hybrid & Pressure Fed Boosters Advanced LOX/LH ₂ Upper Stage Engine Electric Propulsion (Solar & Nuclear) Cryo Storage & Management Leak-free Tubes & Flanges Adaptive, Fault-Tolerant GN&C GPS-based Guidance Electromechanical Actuators/PMAC Automated Health Monitoring Low-cost Al-Li Alloy Structure/Cryo Tanks Low-cost Composite & Metal Matrix Structure/Tank Advanced Manufacturing Processes & Welding Computer Integ. Design, Manufacturing, & Test Automated Pre-Post Flight Data Analysis

3.6 Bridging Activities

It is recognized that mechanisms must exist to "bridge" the gap between traditional technology development in OAET and major user code advanced development programs. The overall NASA Technology Maturation Process steps are depicted in Figure 3-6. These nine levels of technology readiness are then mapped to areas of responsibility within NASA as defined by the NASA technology maturation strategy shown in Figure 3-7. The early levels of technology growth are conducted in the R&T Base program in a technology "push" mode. This is primarily work not focussed toward an immediate specific user need but rather anticipates future technology needs for various user programs. As the technology matures, it may be brought into the Focused R&T program (one of the five thrusts, i.e. transportation, science, platforms, exploration or operations) in a technology "pull" mode focussed toward a user-defined need. The next step is the most difficult, that of "bridging" between the the OAET R&T responsibility of technology development and the user office responsibility of advanced development to mainline into an actual flight program. The Strategic Avionics Technology Working Group (SATWG) initiated at Williamsburg in November 1989, the Space Propulsion Synergy Group growing out of the 1990 Penn State Symposium and the September 1991 Materials & Structures Workshop represent a major step in such bridging activities. Tasks must be carefully selected for well-defined cooperative activities shared by OAET and the user office to enable the transition of the technology into the flight program office's advanced development program.

The Office of Space Flight Advanced Program Development Office emphasizes concept definition, system definition and advanced development for space transportation, advanced operations support systems and advanced space systems. In advanced transportation, studies will continue to assess concepts for the next generation of manned vehicles, including two-way personnel transportation systems and advanced manned transportation systems. In support of the NLS, definition studies will be conducted on the CTV and advanced upper stages. Growth versions of NLS and alternate concepts will be studied to support heavy-lift capability trade analyses for future exploration missions. Advanced development activities will be continued in the areas of autonomous rendezvous and docking; adaptive guidance, navigation and control; electrical actuators; vehicle health monitoring; and fabrication techniques of advanced structural materials. New advanced development efforts will be initiated based on high priority areas identified in FY 1992 studies.

Figure 3-6
THE TECHNOLOGY MATURATION PROCESS

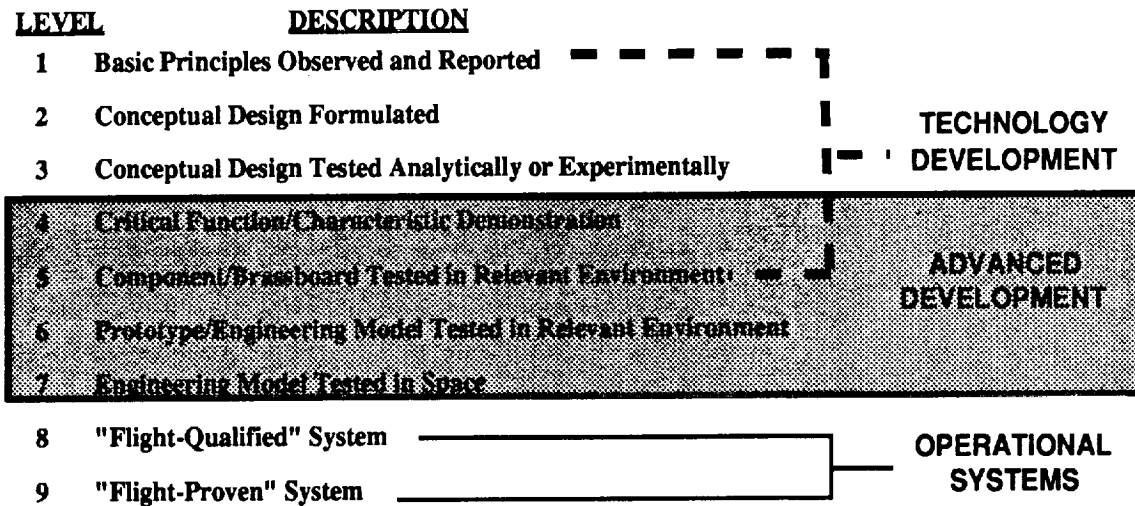
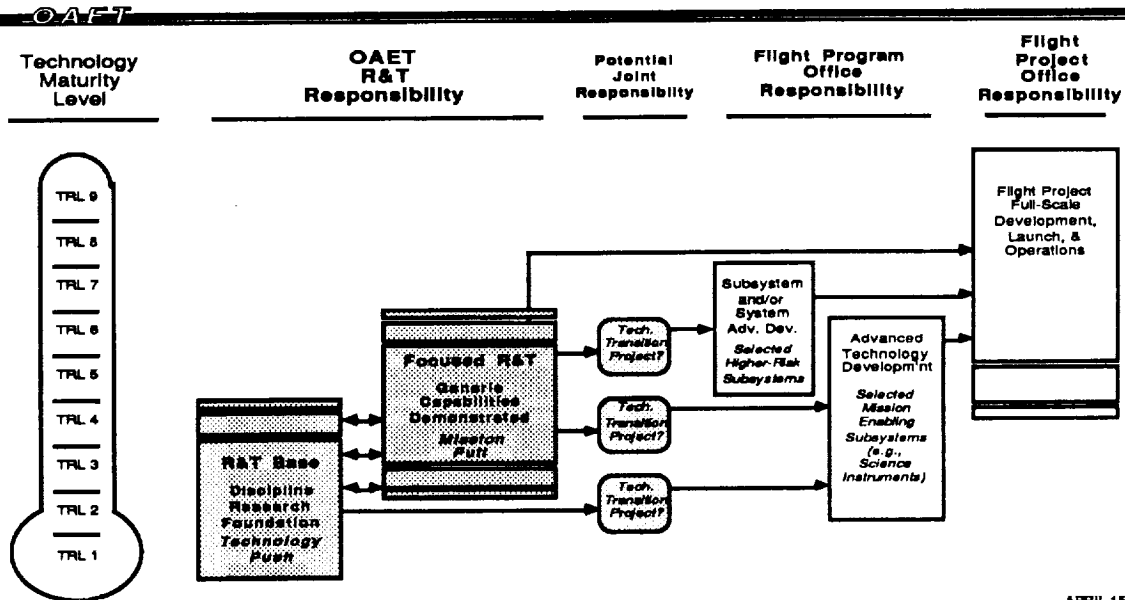


Figure 3-7
TECHNOLOGY PLAN FOR THE CIVIL SPACE PROGRAM
NASA TECHNOLOGY MATURATION STRATEGY



APRIL 15, 1991
JCM-70796

CHAPTER 4

Transportation Technology Program Plan

4.1 Overview

The Transportation Technology Program Plan is a strategic plan. It attempts to address all of the critical technology needs from each NASA user organization [Office of Space Flight, Office of Space Science and Applications, Office of Space Operations, Office of Exploration] as well as the needs of the commercial transport industry in the U.S. Several of the technology elements are currently funded while others will be initiated as funding permits. Within each of the technology areas (i.e., *ETO Transportation*, *Space Transportation and Technology Flight Experiments*), each element is discussed in detail under the following common headings:

- **Overview:** provides a general description of each program element, identifies the application of each element to mission needs, specifies a key objective for each program element and subelement, and discusses the state-of-the-art of the technology addressed by each element.
- **Current & Related Programs:** gives a general description of the current status of each program element, and identifies subtasks and centers currently involved. Discusses related technology development activities for each program element.
- **Proposed Technology Program:** details the proposed technology program for each program element, addressing proposed objectives, subelements, milestones and involved centers.
- **Summary of Technology Program Benefits:** discusses the benefit, in terms of mission requirements, of each program element.

4.2 Earth-to-Orbit Transportation

- 4.2.1 Overview
- 4.2.2 ETO Propulsion
- 4.2.3 ETO Vehicle Structures & Materials
- 4.2.4 ETO Vehicle Avionics
- 4.2.5 Low-Cost Commercial Transport
- 4.2.6 Potential Future Augmentation

4.2.1 Overview

The term "Earth-to-Orbit Transportation" as employed here refers to transportation vehicles used to deliver people and/or cargo from the earth's surface to low Earth orbit. Overall technology advances are needed to: extend current capabilities; improve reliability, safety, performance and efficiency of systems; and reduce support requirements and streamline operations where significant cost improvements could be realized. The objective of the Earth-to-Orbit Transportation area is to develop and validate technologies that improve existing systems and enable new design-to-cost vehicles.

ETO propulsion technologies are needed to support propulsion needs of Space Shuttle

evolution as well as the Heavy Lift Launch Vehicles, including the Advanced Manned Space Launch System. Advances in structures and materials are required to reduce or minimize mass and manufacturing costs. Avionics technology advances are needed to reduce pre-launch vehicle checkout costs, to provide fault-tolerant systems and to minimize operational costs.

These technology needs for each of the user vehicles / systems are shown in matrix format in Figure 4.2-1 and a summary of the key technologies to be pursued within each of the program elements is shown in Figure 4.2-2 as a prelude to discussion of the individual technology program elements.

Figure 4.2-1
ETO User Vehicle Technology Requirements / Applications

Technology Element \ User Vehicle/ System	Space Shuttle Evolution	Personnel Launch System (PLS)	National Launch System (NLS)	Advanced Manned Launch System (AMLS)	Commercial/ Expendable Launch Vehicle (ELV)
• ETO Propulsion	X		X	X	X
• ETO Vehicle Structures and Materials		X	X	X	
• ETO Vehicle Avionics	X	X	X	X	
• Low-Cost Commercial Transport					X*

* note: could also support alternate technologies for NASA user systems

Figure 4.2-2
ETO Technology Program Elements

<p align="center">ETO Propulsion:</p> <ul style="list-style-type: none"> Combustion Devices <ul style="list-style-type: none"> Advanced Main Combustion Chamber Experimental Validation of Combustion & Stability Codes Health Monitoring and Control <ul style="list-style-type: none"> Electronic Engine Simulation EMAs for Advanced Thrust Vector Control Post-Flight Maintenance Expert System In-Flight System Monitoring Pre-Flight Servicing & Checkout System Monitoring Integrated System Monitoring and Control Propulsion System Studies <ul style="list-style-type: none"> Viable AMLS Propulsion System Concepts Advanced Engine Cycle & Multi-Nozzle Optimization Turbomachinery <ul style="list-style-type: none"> Fluid Film Bearings 3D CFD Codes of Internal Engine Flow Processes Advanced Materials & Processes <ul style="list-style-type: none"> Ceramics Composites 	<p align="center">ETO Vehicle Avionics:</p> <ul style="list-style-type: none"> Avionics Architecture Avionics Software Vehicle Health Management Guidance, Navigation & Control <ul style="list-style-type: none"> Adaptive 1st Stage Steering Advanced Control Laws Sensor Evaluation & Development Electrical Actuation <ul style="list-style-type: none"> Fault-tolerant 40 HP ELAs Landing/Recovery Systems <ul style="list-style-type: none"> Large-scale Gliding Parachute Parachute CFD Codes Sensors to Measure Performance Propulsion System Recovery Module Closed Recovery Module Door Power Management & Control <ul style="list-style-type: none"> Advanced Power Backbone
<p align="center">ETO Vehicle Structures and Materials:</p> <ul style="list-style-type: none"> Materials Characterization <ul style="list-style-type: none"> Al-Li Alloys Resin Matrix Composites Structural Design/Analysis <ul style="list-style-type: none"> Integrated Thermostructural Design/Analysis Low-Cost Processing & Fabrication <ul style="list-style-type: none"> Al-Li & Resin Matrix Composite Structures & Cryotanks Real-time NDE for Weld Inspection NDE for Composite Structures/Cryotanks Sub-component Design, Fabrication & Test 27.5' Diameter Tank w/ Single Barrel Section 	<p align="center">Low-Cost Commercial Transport:</p> <ul style="list-style-type: none"> Propulsion <ul style="list-style-type: none"> Low-cost H₂ & Hydrocarbon-fueled Liquid Engines Low-pressure Liquid Booster Engines Hybrid Engines Solar-Thermal OTV Engines Avionics <ul style="list-style-type: none"> Advanced Architectures Avionics Software Vehicle Health Management (VHM) GN&C Power Management & Control (PMAC) Structures & Materials <ul style="list-style-type: none"> Al-Li Cryotankage, Roll Forging, Spin-Forming Built-up Structure, Net Section Extrusion Low-Cost Composites Automated Inspection and NDE Computer Integrated Manufacturing Automated Welding

4.2.2 Earth-to-Orbit Propulsion

Overview:

The ETO Propulsion Technology Program is a joint MSFC/LeRC technology activity which primarily addresses reusable, pump-fed, cryogenic engine component and subsystem technology. The primary objective is the technology development that will enable ETO propulsion systems with high reliability, high design margins & service life, autonomy in ground & flight operations, reduced costs and higher performance. Major components are advanced turbomachinery, combustors, system monitoring, validated design methodologies & tools and manufacturing processes as well as advanced concepts which will enable routine, affordable access to space. Also addressed is the continuing enhancement of knowledge, understanding and design methodology applicable to the development of advanced oxygen/hydrogen and oxygen/hydrocarbon ETO propulsion systems. The Earth-to-orbit Propulsion Technology Program addresses Space Shuttle evolution, commercial/ELV, PLS, HLLV, and AMLS requirements.

Current & Related Programs:

The ETO propulsion program is currently divided into a Technology Acquisition phase comprised of 10 scientific and engineering discipline working groups, and a Validation phase of three categories of focused subsystem effort. The working groups are:

Bearings	Structural Dynamics
Turbomachinery	Fatigue/Fracture
Combustion	Fluid Dynamics
Instrumentation	Controls
Manufacturing	Materials

The three validation categories are: Combustion Devices, Turbomachinery, and System Monitoring and Controls. Some 200 individual tasks comprise the total program.

The objective of the program is to provide the knowledge, understanding, and design methodology that will enable the development of highly reliable, cost effective ETO propulsion systems. These advanced propulsion systems should enjoy high performance and long service life along with sharply reduced development and production costs, and reduced program risk. The element is aimed at providing flight-systems with needed propulsion, ground-test-verified advanced component/subsystem technologies, analytical/design tools and materials and fabrication processes for all civil U.S. Earth-operated space transportation systems.

Major components of the program are:

Analytical models - for defining engine environments and for predicting hardware life [flow codes, loads definition, material behavior, structural response, fracture mechanics, combustion performance and stability, heat transfer]

Advanced component technology - [bearings, seals, turbine blades, active dampers, materials, processes, coatings, advanced manufacturing]

Instrumentation - for empirically defining engine environments, for performance analysis and for health monitoring [flow meters, pressure transducers, bearing wear

detectors, optical temperature sensors]

Engineering testing - at subcomponent level to validate analytical models, verify advanced materials and to verify advanced sensor life and performance.

Component/test bed engine - for validation/verification testing in true operations environments.

The current focused technology program has been in place since 1988. Close ties are maintained between LeRC, MSFC and NASA Headquarters by scheduled reviews and day-to-day informal contacts. The program provides generic technology to the user community; however, user needs are addressed in the program. This is accomplished by means of formal reviews and other interchanges with the user community programs. In addition, the user needs/technology availability interaction is facilitated by the fact that the technologists are also working day to day Shuttle engine problems and are involved in the development of new engines, such as the STME for the NLS program.

There are several related areas to the ETO program and full interchange of its technology content is mandatory. For example, the joint NASA/USAF NLS is developing low cost cryogenic propulsion systems, where performance is secondary to cost. The Advanced Cryogenic Engines program in the Space Transportation Area is a NASA upper stage and space vehicle engine technology development program. The SDIO (Strategic Defense Initiative Office) is pursuing a single-stage-to-orbit vehicle. The propulsion system for this vehicle requires very high performance. The technology arising from the ETO program should benefit all these programs.

Proposed Technology Program:

The current and planned activities of the ETO Propulsion program are summarized by major area of technology which then feed into the three technology validation activity areas.

The Bearings activity primarily covers technology associated with rolling element bearings. Disciplines such as heat transfer, lubrication and fluid dynamics are all part of the bearing technology project. Great difficulty has been experienced in the past with operating bearings in the harsh environment of a liquid oxygen turbopump. LOX is a poor lubricant itself and is incompatible with most lubricants. The problem is particularly severe for reusable engines. The Space Shuttle engine bearings are normally replaced at great expense after one or two flights. Bearing testers are in use in this project which have demonstrated greatly increased bearing life for advanced concepts. Efforts are underway to validate these concepts in an actual turbopump application.

The Structural Dynamics activity is largely analytical in nature and addresses structural effects of acoustics, fluid flow and other driving mechanisms. There is also significant effort in this working group on probabilistic structural analytical techniques. Probabilistic methods applied to loading spectra, thermal/mechanical properties and material degradation properties. These methods are critical to avoid excessive conservatism in advanced high performance propulsion systems.

The Turbomachinery area provides computer modeling codes and methodologies pertaining to Turbopump systems. Some experimental work is also being accomplished toward hydrostatic bearings. Advanced seal work is also underway which has a goal of drastically reducing the quantities of purge gases currently used by flight systems. This activity leads into a series of validation activities. Among these are water and airflow test rigs, a proposed turbopump test stand and the Technology Test Bed (TTB), a highly instrumented

SSME engine which is used to provide a complete engine system for validation of those technologies must have a complete system for adequate validation.

Fatigue/Fracture: This is a largely analytical activity, the effort is broadly divided into crack initiation and crack propagation prediction. Much of the current technology is directed toward anisotropic materials (composites) and the study of crack initiation/propagation in the plastic region. Some effort is also underway to establish better proof test criteria, such as number of cycles at which levels of proof are required adequately prove a component. Since fracture propagation ultimately results in failure, validation of this technology is usually accomplished by evaluation of failures in test components. This technology is often applied to estimates of remaining life in test and flight hardware.

Combustion: The Combustion working group is concerned with all aspects of the combustion/ignition process, combustion stability, combustion energy equations, chamber cooling and chamber manufacturing are all addressed in this working group. There is also some hydrocarbon combustion technology in this working group. The manufacturing effort centers around Flatlet technology (chamber and/or injectors fabricated from stacks of thin plates incorporating appropriate cooling slots and flow passages), Vacuum Plasma Spray techniques and advanced casting techniques. The manufacturing activity arises from the great cost and long lead times associated with current Main Combustion Chambers. Chamber life extension is also under investigation through improved liner materials and improved cooling passage design. A significant cause of short chamber life being fractures forming around cooling slots.

The **Fluid Dynamics** tasks primarily deal with advanced analytical techniques concerning turbomachinery. Heat transfer and unsteady flow conditions are also part of this activity. This working group also sponsors a very significant activity in Computational Fluid Dynamics. CFD teams of investigators from government, industry and universities are comparing existing codes, evaluating new codes and applying the best codes to real world problems. Three teams have been set up for Turbines, Pumps and Combustion. As in Turbomachinery, validation is accomplished by means of air and water flow tests. The proposed Turbopump Test Stand will permit full scale validation at the correct environments. At the present time, TTB data provides some validation but instrumentation is limited and the engine must be run at more or less nominal conditions.

The **Instrumentation** activity provides advanced instrumentation to obtain measurement of engineering parameters previously unobtainable. The emphasis is on finding non-intrusive or minimally intrusive instruments that can be installed to take measurements in locations which have previously defied instrumentation. Examples are LOX flow measurements and temperature/heat flux measurements on turbine stators. An area of particular interest to the flight programs is an investigation into sensor self diagnostics which notify the control system when the instrument is no longer working properly.

The **Controls** activity attempts to develop new and improved methods of engine control. This includes engine controller software and hardware that supports advanced health monitoring and diagnostics. Other aspects of engine control are also included such as electromechanical actuators and electric motor technology. Advanced data storage for the mass of test and flight data generated by an active development and operational program is also being investigated. Both optical and solid state techniques are being studied. This program has initiated an electronic engine simulation system to evaluate health monitoring & control software and hardware over a wide range of both design-normal and anomalous or off-nominal conditions. This laboratory system is usable at present, but will require upgrades.

The Manufacturing activity is closely coordinated with the Combustion tasks by providing the vacuum deposition capability for fabrication of the advanced main combustion chamber. In addition there is also vacuum deposition work which has identified coating techniques which, if applied to SSME type turbine blades, could greatly extend life and possibly increase performance by 2 or 3 percent. Ceramic engine component and ceramic composites are being studied as well as non-destructive evaluation techniques.

The Materials effort is generally divided into near term technology issues facing the on-going flight programs and longer range technology. The near term technology covers such items as advanced bearing materials, advanced turbine blade materials, and effects of hydrogen on materials. The longer range activities are associated with fiber reinforced alloys and advanced copper alloys.

Combustion Devices Validation is accomplished through subscale motor firings and full scale engine firings. An informal agreement has been established to focus on subscale motors in the 40,000 lb thrust range for screening tests. Motors of this size are in use at present. For validation at full scale, the present plans call for use of the TTB.

Turbomachinery Validation employs a wide array of subscale and alternate environment test facilities, these include bearing testers, turbine blade testers, air flow facilities and water flow facilities. At the other end of the validation spectrum is the TTB which is a full scale SSME. While the TTB is the most realistic environment available for validation of technology it has a relatively long turn-around time and as a complete system must operate at a single point. In addition, since the TTB and test stand represent an investment of 40 to 50 million dollars high risk, high-payoff technology is sometimes difficult to incorporate. For these reason a turbopump test stand that can be dedicated to technology as opposed to flight programs is needed. This facility is planned to become operational in 1995.

System Monitoring Validation is concerned with the Acquisition phase of the ETO program which is developing advanced software and hardware for rocket engine control. This new architecture is designed to provide a higher degree of safety to the crew and vehicle with reduced probability of erroneous shutdown. To some degree these new systems must be designed based on past engine failure experience. Since it is not practical to introduce new failures into an actual engine firing to challenge the new monitoring systems, the monitoring system is challenged electronically in engine simulation facilities. Thus a large number of potential failures can be tested over a range of engine operating conditions. the propensity for incorrect shut-offs can also be addressed. Competing software and hardware can be given fair comparisons in the simulation labs. The initial simulation capability exists at present with a full-up capability expected by 1994.

Ultimate validation will occur on TTB, initially the monitoring equipment will be installed on the TTB stand and will function in a MONITOR ONLY MODE. After the system has demonstrated safe operation without inadvertent shut-downs, it will be allowed to interface with the engine controller in an operational mode.

The approach of the ETO program is to utilize a broad base of national expertise via competitive contracts, as far as possible, with prime engine, other aerospace (as well as non-aerospace) contractors, academia, and government research facilities.

The ETO propulsion technology program addresses both LOX/LH₂ and LOX/Hydrocarbon propulsion technologies. The overall goals of the proposed Earth-to-Orbit Technology Program are to:

- Support Space Shuttle propulsion system overall new-technology needs (past/present to end of STS evolution activities)
- Support commercial/expendable launch vehicle propulsion system overall new-technology needs (near term future to ultimate phase-out period)
- Support personnel launch system propulsion system overall new-technology needs (near term future to phase-out)
- Support heavy lift launch vehicle propulsion system overall new-technology needs (near term future to ultimate phase-out period)
- Support advanced manned space transportation system propulsion system overall new-technology needs (ca. 2005)

The program should continue driving toward validated technology. Some two dozen ETO technology items have been approved for validation testing on the Technology Test Bed (TTB) in FY 92 and beyond. As mentioned earlier, other validation testing is underway at present. The electronic simulation laboratory will be complete in FY 92 or 93, and a variety of engine control and health monitoring algorithms validated. A large-scale turbopump stand is badly needed to test high risk-high payoff technology items. This facility is planned for FY 94-95. The initial activities supporting system studies and non conventional approaches such as single pumps feeding multiple chambers, aerospike nozzle, oxidizer rich technology should be pursued.

The long term program plan is to develop a national infrastructure of analytical and design tools, competent engineers and test facilities to assure rapid, efficient development of high quality, producible, propulsion systems to meet future national requirements regarding performance, safety, cost and schedule. This includes advanced manufacturing processes and design methodologies applicable to fully reusable, long-life AMLS propulsion and demonstrating propulsion system monitoring and control for automated operations.

Summary of ETO Propulsion Technology Program Benefits:

The ETO program is the only broad-based propulsion technology program in the United States which addresses the perpetual needs for high performance and lower cost for space transportation propulsion systems. It is the only such propulsion technology program supporting the STS, HLLV, ELV and commercial ELV. The program will provide advanced analytical techniques, advanced manufacturing techniques, improved design approaches, and control software and hardware. The products will be validated at appropriate scale and provided to the user community in a timely manner. Space transportation systems will benefit from advancements in propulsion system performance, service life, and automated operations and diagnostics.

4.2.3 ETO Vehicle Structures & Materials

Overview:

The objective of the ETO Vehicle Structures & Materials program is the realization of weight and cost savings through advanced metal alloys & composites coupled with efficient fabrication as well as automated processing and test. The program is focused on the development and validation of a technology base that will provide weight and cost

savings of 20 to 40 percent compared to conventional technology in the fabrication of cryotank and vehicle structures for Earth-to-orbit transportation systems. Weight savings will be achieved through the use of advanced materials and efficient design. Cost savings will result from the use of advanced fabrication methods coupled with lighter weight materials for reduced system costs. Key supporting technologies include aluminum-lithium alloys and composite materials for lightweight cryotank and the associated manufacturing technology for component fabrication. Other supporting technologies include but are not limited to development and verification of structural integral design and analysis methods, cryogenic insulation and thermal protection systems.

Current & Related Programs:

There is no current OAET focused technology program for ETO Vehicle Structures & Materials Technology. Related activities include the NLS Advanced Development Program, the High-Speed Civil Transport program in Aeronautics, and the supporting Space R&T Base Program in materials and structures.

Proposed Technology Program:

The proposed program focuses on the development of lightweight materials and structures that may be enabling technologies relative to achievement of payload weight to orbit, design margins and systems cost goals for ETO systems. Subelements include materials characterization, structural design and analysis, low-cost processing and fabrication development, and sub-component design, fabrication and test. Participants include Langley Research Center as overall element lead, Marshall Space Flight Center, Johnson Space Center and Ames Research Center.

The materials characterization subelement activities will be led by LaRC and supported by MSFC. Objectives include the characterization and selection of candidate Al-Li alloys and resin matrix composite materials that offer a 15 - 30 percent improvement in specific properties compared to conventional aluminum alloys for fabricating primary structures for PLS/AMLS vehicles and cryotanks for ETO transportation vehicles. The existing database and the database under development for NLS will be examined and expanded as required. Data will also be generated as required to determine the effects of processing on material properties.

The structural design and analysis subelement will be led by LaRC and supported by ARC and Ames-Dryden. The objectives are to develop a truly integrated thermostructural design/analysis capability for AMLS and to investigate the structural ramifications of new materials/fabrication methods applicable to PLS and other launch vehicles. The thermostructural analysis work will include TPS and primary structures as a thermostructural entity.

The low-cost processing and fabrication development subelement will be led by MSFC. The objective is to develop a technology base to provide for the fabrication of low-cost lightweight Al-Li and resin matrix composite vehicle structures and cryotanks. Validate the technology through the design, fabrication and testing of structural sub-elements. Innovative processing methods such as superplastic forming net section extrusion, spin forming, explosive forming, laser welding, variable polarity plasma arc welding, and resistance welding will be evaluated for metallic components and filament windings of wet and dry resin matrix composites, automated tape lay-up and resin transfer molding for composite components. Cost trade studies will also be conducted to assess cost benefits as will identification of real-time NDE methods for weld inspection and identification of available NDE methods for composite structures and cryotanks.

The sub-component design, fabrication, and test subelement will be led by MSFC and supported by LaRC and JSC. The objective of this technology subelement is to validate the materials processing and design elements through the testing of moderate size components. The cryotank technology will be demonstrated by the design, fabrication and test of a large diameter tank having a single barrel section. Plans are to evaluate tasks underway in the NLS Advanced Development Program (ADP) and build on both near-term and far-term cryotank technology using Al-Li alloys. Point designs for personnel launch carriers will be fabricated and tested. Sub-scale composite material intertank and payload shroud structures will be designed, fabricated and tested.

Summary of Structures & Materials Technology Program Benefits:

This technology program will provide weight and cost savings of 20 to 40 percent compared to conventional technology in the fabrication of cryotank and vehicle structures for Earth-to-orbit transportation systems. It will provide enabling technology for the AMLS.

4.2.4 ETO Vehicle Avionics

Overview:

The next generation of space transports will need to be designed and qualified to maximize crew safety and ensure mission success. These transports will be automated to the fullest extent practical so that the crews may concentrate their efforts on tasks requiring human attention. In addition, the energy conservation requirements will require a high degree of efficiency in virtually all vehicle systems, thus placing more stringent design requirements upon them. This, in turn, will force the development of new technologies needed to meet those requirements. The objective of the ETO Vehicle Avionics program is the removal of most weather constraints, greatly reduced turnaround times, automated operations and highly fault tolerant & low maintenance systems.

Avionic systems for advanced Earth-to-Orbit (ETO) and Transfer Vehicles will require technological development in the following areas:

- Avionics Architecture - for increased avionics performance
- Avionics Software - addresses mission and safety features in software operating systems kernel
- Vehicle Health Management - for self-diagnosing and self-compensating integrated systems
- Power Management and Control - for reliable, universal, modular, electrical power bus systems
- Guidance, Navigation and Control - offers enhanced capabilities in space platforms, electrodynamic propulsion, momentum transfer
- Electrical Actuation Systems - replaces hydraulic systems to enhance system reliability, reduced processing
- Advanced Landing & Recovery Systems - to resolve for booster recovery technologies

Inasmuch as ETO and Transfer Vehicle avionics are required to perform many of the same or similar avionic functions, the development of their technologies can in many instances be shared. In other words, there should be a "technology transfer" between the developing technologies of the respective vehicle hardware and software systems, subsystems and

components.

Current & Related Programs:

There is no current avionics focused technology program in ETO. This element is a proposed new element. Related programs will be discussed in the context of the proposed technology program.

Proposed Technology Program:

The Strategic Avionics Technology Working Group will be used in coordinating the advanced **Avionics Architectures** needed for the next generation of ETO vehicles. It will act as a forum for debating, recommending and advising the avionics community as needed to:

- Determine requirements which will drive the architecture development
- Identify appropriate standards of architecture development
- Develop the architecture required for each avionic function
- Identify critical areas within the architecture which will require significant technology development
- Identify trends and developments in industry which are applicable to NASA programs.
- Implement the architecture in test beds within NASA and industry to prove out the concepts.

The development of Avionics Architecture for a next generation ETO vehicle calls for the development of requirements and specifications appropriate to the demand for improved versatility, performance, reliability and efficiency. Development of these requirements will be achieved through a variety of analyses, including test bed networking, configuration and interface studies. The system architecture developed will be applied first to simulated models of typical ETO hardware and software elements. Then, as specific hardware components and software programs for a given ETO application become available, prototyping will be possible.

In the approach to avionics architecture development indicated above, the unique requirements of "open" avionics architectures, capable of integrating a variety of avionics systems, will be addressed. Among the principal aims of such an approach is achievement of the maximum possibility of re-use. Clearly re-application of the same architecture to different systems will require standardization of system, subsystem and component interfaces.

The major goals of **Software Design** are simplicity and reliability while maintaining the versatility and efficiency required for optimum performance of the many avionics tasks. Included in the areas of investigation addressed by avionic software research and development are those software applications specifically directed to flight safety. Effective fault detection, isolation and recovery (FDIR) will continue to be an area of challenge to engineers and software designers.

Current Vehicle Health Management technology activities are centered around

identification of promising ventures, development of generic VHM functional requirements, and the identification of insertion targets for VHM constructs (e.g. Space Shuttle upgrades and enhancements). In general, VHM encompasses development of subsystem, system, and vehicle level status determination, fault tolerance, and reconfiguration techniques for a self diagnosing and self correcting integrated system. VHM development is a candidate technology bridging (linking Code M and Code R objectives) initiative to be shared by JSC, KSC, and MSFC.

Current areas of investigation for ETO include system architecture, development of sensors, and development of supporting software. Current automatic checkout and health maintenance capabilities are limited in their abilities to assure safe and reliable on-time launches and in-flight operations. These current capabilities will be enhanced by:

- development and assessment of new sensors which are capable of detecting equipment performance changes under extreme dynamic conditions
- development and demonstration of architectures which can enable maximum benefit of existing check-out and maintenance capabilities along with the introduction of new capabilities and technologies
- establishing the software which will connect and coordinate the present capabilities and technologies along with the architecture and new sensors that are developed.

Current NASA areas of investigation for GN&C algorithm development are concerned with Autonomous Launch Vehicle reconfiguration, advanced GPS navigation techniques and autonomous rendezvous/docking GN&C. The primary emphasis behind these is a desire to develop GN&C related methods and approaches which reduce operations costs while maintaining vehicle safety and mission availability. For Space Shuttle, improvements have been identified such as Day of Launch I-Load Update which reduces the requirement for trajectory re-design on a mission to mission basis. The GN&C Bridging Task has made progress in assessing the usefulness of advanced upper atmosphere wind measurement sensors such as LIDAR and radar wind profiler and the best current methods for providing in-flight load relief for aerodynamic structural loads. GPS navigation and autonomous rendezvous and docking have been identified as areas with high potential for improvements in operations costs.

For ETO applications, the primary thrust of **Electrical Actuation (EA)** technology is the development of systems to replace conventional servo-hydraulic centralized hydraulic systems. As such, EAs will provide the motive force behind aerosurfaces, engine gimbal systems for thrust vector control (TVC), engine control valves, and propellant and other fluid system control applications. EA technology will enhance system reliability and reduce launch processing and other servicing requirements compared with the centralized servo-hydraulic systems.

The EA technology development program is predicated upon realizing the maximum possible leverage from significant developments in industry and the NLS Advanced Development Program and applying these developments to unique NASA requirements. The Electrical Actuation element includes the following general goals:

- development of fault tolerant ELAs with demonstrated performance, reliability, and tolerance for the high duty cycles characteristic of a prime flight critical application

- definition and assessment of requirements and systems concepts for the boost segments of advanced NASA/Military/Commercial programs
- laboratory and test bed demonstrations of linear and rotary direct acting devices (EMAs), EHAs, and a brassboard demonstration of the basic principles underlying a magnetostrictive actuator servovalve

Current NASA areas of investigation for **recovery systems** include the development and demonstration of large scale gliding parachute systems for recovery of booster components. Since flexible structures are difficult to scale, parachute systems must be demonstrated at full scale to provide a quantifiable system. Inflation, steady glide, and landing flare will eventually be demonstrated using a 10,820 square foot Parafoil in the Advanced Recovery Systems Program.

Specific areas of investigation include:

- 1) Parachute Aerosciences
- 2) Advanced Recovery Systems (ARS) Phase IIIA Demonstration
- 3) Parachute Guidance, Navigation and Control
- 4) Impact Systems Test Bed
- 5) Advanced Instrumentation

The objective of current **Power Management and Control (PMAC)** development efforts and studies is to develop and demonstrate a universal, modular, electrical power bus system that will serve as a "*Power Backbone*" to support and integrate upwards with other avionics subsystems and controls, and downwards with all sources and loads, which may be paralleled across distributed, intelligent nodes and interfaces. In the case of a multi-node system implementation, each node will be aware of the existence and operational status of the other nodes.

Other PMAC items of interest include fault-tolerant power bus architectures, autonomous reconfiguration and multi-node neuron chip controls, and end-to-end systems and components including energy storage devices.

Technology Benefits Summary:

Benefits expected from the proposed ETO Avionics Architecture Development Program include additional avionic system capabilities and improved performance. Specific improvements are anticipated in real-time distributed processing, high capacity processing, non-stop computing and avionics displays and controls. Some specific benefits include development of flexible architectures, transfer of commercial data processing components into space-rate processors for compatibility with ground systems, automated vehicle checkout to expedite/minimize pre-launch labor-intensive operations and autonomous vehicle health management to minimize impact of component failures in-flight.

Vehicle Health Management benefits will result from automated vehicle checkout, autonomous vehicle health management, VHM system architecture and software, VHM sensors and residual lifetime estimation, dynamic health and status assessment. These should result in expedited pre-launch operations, improved efficiency and robustness of avionic systems and improved performance margins of systems.

Benefits expected from the proposed GN&C technologies include autonomous launch vehicle GN&C reconfiguration to eliminate manpower-intensive activities otherwise required for the next generation of launch vehicles, ability to adapt to dispersed conditions

in the atmosphere while maintaining an accurate landing point, GPS navigation accuracy which avoid degradation of Doppler measurements caused by changing environmental conditions and autonomous rendezvous GN&C which escape current operations which rely heavily upon ground-based manual procedures. Parallel processing GN&C methods will enable complex GN&C computations with onboard parallel processors.

Technology benefits in the research and development of the proposed guidance and navigation sensors which support ETO missions include optical rate sensors that enable real-time navigation imaging and attitude determination, autonomous attitude determination systems for reliable real-time attitude determination, a terrain mapping/feature recognition system yielding precision navigation capabilities, a magnetoresistive sensor providing azimuth determination packaged for less volume, weight, cost and power consumption, and an interferometric fiber-optic gyro (IFOG) that bears a high mean time before failure angular rate sensor without high voltage.

The Electrical Actuation subelement will enhance system reliability, increase efficiency and reduce weight of actuators through the use of electric motors instead of conventional hydraulic systems. Hazardous fluids and avionics fluid couplings will be eliminated. Benefits will result from work on EMAs and EHAs.

Technology benefits in the development of Landing & Recovery Systems include precision flared landing capabilities and reduction of landing zone requirements by compensation for environmental effects. Technology areas to be worked include parachute aero sciences, the advanced recovery system, parachute GN&C, impact systems test bed, and advanced instrumentation.

The benefits of key PMAC technology elements as they apply to ETO systems include increased fault tolerance and robustness, decreased weight and higher efficiencies. These result from work on autonomous reconfiguration, integrated modular service backbone, high frequency power distribution and control, high energy density battery systems, enhanced fuel cells and advanced energy storage and power conditioning devices with advanced motor controllers.

4.2.5 Low-Cost Commercial Transport

Overview:

The objective of the Low-Cost Commercial Transport Program is to develop and validate industry-driven requirements for propulsion systems, structures, materials & advanced processes, and avionics technologies needed to commercially develop low cost, operationally efficient, ELVs and upper stages. As directed by the "Commercial Space Launch Act Amendments of 1988", the NASA (through the Office of Aeronautics, Exploration and Technology), in conjunction with the commercial launch vehicle industry, will develop a plan for component-level research and technology to reduce initial and recurring costs, increase reliability and improve performance of expendable launch and upper-stage space vehicle systems used for commercial service. Categorically, these technology tasks may be divided into two classes: near-term technology needs in three to eight years and longer-term needs, i.e. beyond the year 2000. The near term will focus on technologies to enhance the existing fleet of commercial launch and upper-stage systems while the longer-term tasks will focus on those technologies that will enable a new generation of cost effective commercial space transportation systems. The technology program defined herein is divided into three principal subelements: propulsion, structures

& materials, and avionics. Technologies may also provide alternative systems for NASA missions and services as a test bed for early validation of technologies.

MSFC will assume the lead role for integrating the overall OAET low-cost commercial transport technology element as well as the lead for developing the propulsion discipline technologies; LeRC will serve as a supporting Center for propulsion (in OAET parlance, the hierarchy of involvement is lead Center, supporting Center and participating Center). LaRC will be the lead Center for commercial vehicle materials and structures with MSFC supporting. JSC will have lead responsibility for commercial vehicle avionics with ARC and LaRC supporting.

Current & Related Programs:

At present there are no on-going or current NASA-sponsored technology development programs specifically focused at the commercial user needs. There are however, several on-going related NASA and USAF programs as well as the Independent Research and Development activities underway at each of the commercial vehicle system contractor facilities focused on their respective commercial interests. This IR&D work and the associated financial resources are a vital asset and must be integrated into the planning process of this NASA-sponsored commercial R&T program.

In addition, there are several joint (NASA/Industry) activities on-going at NASA Centers that operate under the provisions of the 1988 Space Act Agreement. These are typically technology verification activities whereby NASA provides facilities, equipment and engineering support to Industry on a no charge, no cost basis in exchange for access to the emerging new technologies of mutual interest. Some examples of these activities are the manufacturing and processes IR&D validation work carried out at the NASA/MSFC Productivity Enhancement Center and the TRW-Pintle injector development tests and foil-bearing development tests at NASA/LeRC. Other NASA facilities such as the Stennis Space Center Component Test Facility may also be utilized.

With regard to current related technology development programs, two stand out as being germane to the interest of commercial space transport: (1) the Earth-to-Orbit Propulsion Focused Technology Program (see paragraph 4.2.1, this document); and (2) the USAF/NASA - National Launch System Advanced Development Program. Other programs (e.g. Advanced Cryogenic Engines) may also make significant contributions.

The NLS-ADP focuses at developing and demonstrating those techniques, processes and methods that will reduce the design development, and operating cost of unmanned cargo launch vehicle systems. The ADP does contain elements of specific interest to the commercial launch community in each of the propulsion, materials and structures, and avionics areas. Some relevant examples are: efforts to advance low-cost, oxygen/hydrogen gas generator cycle engine system known as STME; utilization of roll-forging, net section extrusions and/or built-up structure methods to fabricate low-cost, light-weight aluminum-lithium cryogenic tankage; and the development of advanced avionics architectures to enable the desired reliability/cost goals, the development and implementation of advanced electromechanical actuators (EMA), and the use of advanced automation software to enable integrated vehicle health monitoring/management.

Proposed Technology Program:

The recommended first step in formulating a comprehensive program plan will be to conduct a joint government/industry workshop for the purpose of defining, scoping,

prioritizing, costing (ROM) and scheduling the appropriate subelement tasks. It is imperative that the commercial/industrial community participate vigorously and aggressively in this process to ensure establishment of the proper requirements and tasks definition.

The proposed program subdivides the low-cost commercial transport element into three subelements with a host of tasks to be defined beneath each subelement. The three subelements are: Propulsion, Materials & Structures, and Avionics. The tasks defined thus far have been synthesized from the NASA July 1990, Expendable Launch Vehicle Technology Report to the U.S. Congress; the October 1990 COMSTAC report on "NASA Component Technology Plan" for ELVs and from dialogue with representatives from the commercial launch vehicle industry. The specific tasks will be mutually define with industry. The following is a synopsis of the three subelements.

Commercial Vehicle Propulsion

Those technology tasks that will most effectively enhance the existing fleet of commercial ELVs will be those than can reduce the propulsion system design, manufacturing and operations costs. Technologies that will enable new engine designs such as low-cost, reliable, robust hydrocarbon engines are most attractive and may include advancements like ablative thrust chambers and nozzles using radiation/heat sink and/or film cooling techniques. Other considerations which will allow improvements in current engine designs are low-cost injectors, turbomachinery and thrust vector control, as well as the maximum utilization of electromechanical actuators where possible. Such advancements when coupled with the evolving low-cost manufacturing techniques and vehicle health monitoring/advanced avionics will collectively equate to a lower cost core vehicle/booster system.

Considering upper stage propulsion requirements where engine system performance efficiency, simplicity of design/reliability, and cost of manufacturing and operations are the driving criteria, it is apparent that those technologies that will assure the timely development of medium thrust (35,000 - 200,000 lb) O₂/H₂ expander cycle engines would be of significant value to the commercial space community.

Technology developments that will enable a new generation of first stage, strap-on boosters to replace existing solid systems may be a third category of propulsion-oriented technologies worthy of development. This work would be focused at enabling and demonstrating at sufficient scale, both low-pressure pump-fed liquid boosters and hybrid (solid/liquid) booster systems. Each of these concepts would yield cost competitive alternatives to existing solid motor systems with significant improvements in safety, performance, cost and environmental impact. Hybrids may also be an attractive upper stage propulsion option for select missions

Commercial Vehicles Structures and Materials

Within this subelement there will be tasks to investigate the metallurgical processes and material properties of advanced metallics like Al-Li and Mg-Al-Li high strength lightweight alloys. Select composite material types using low-cost assembly techniques will also be investigated and characterized. In addition to the material investigations, there will be emphasis placed on low-cost manufacturing techniques, processes and methods. Tasks in roll forging, spin-forming and built-up-structure will be advanced. Computer Integrated Design & Manufacturing (CID/CIM) and automated inspection are areas that can effect cost savings to the commercial manufacturer. Low-cost composite structure

manufacturing techniques employing fully automated 'fiber placement' build up with nonautoclave curing processes using thermoplastic resin systems promise to provide improved structural performance with a reduction in cost to the total vehicle system.

Commercial Vehicle Avionics

Tasks within the Avionics subelement will focus on the development and verification of advanced avionics architectures for both on-board flight and ground operations systems. Such architectures will be modular in both hardware and software design and will be highly integrated to form network systems capable of optimizing the reliability/cost ratio. For commercial systems, emphasis will be on eliminating or minimizing the human function in vehicle checkout and flight operations and to provide automated fault-tolerant operations at an acceptable cost. The network systems developed through these advanced architectures could include the integration of vehicle health management, guidance, navigation and control and vehicle power management functions into the master flight operations algorithm.

Summary of Low-Cost Commercial Transport Technology Program Benefits:

The Low-Cost Commercial Transport Technology Program is, in the near-term (3-5 years), focused on delivering for systems level validation testing, those relevant technologies that are currently in work or are resident in the technology reservoir. Emphasis will be on advancements in design, manufacturing and operations that can significantly reduce the ELV systems recurring costs. Advancements in the discipline of low-cost propulsion technologies is perceived to provide the maximum cost benefits when applied as enhancements to the existing fleet of ELVs. Technology advancements in materials and structures and/or processes and avionics will be selected for development on the basis of "return on investment".

The technology products will include advanced design approaches, improved analytical and manufacturing techniques, improved operations and software architectures/methods. The long-term (1998 and beyond) program objectives will focus on providing the technological advancements required to ensure the successful design of the next generation of truly low-cost commercial ELV systems that will operate well into the next century. Studies sponsored during the near-term program will define the components of technology required to enable/ensure the development of the next generation.

4.2.6 Potential Future Augmentation Element

Another element to be considered in the future is auxiliary propulsion. Future vehicle systems including the AMLS will require a new auxiliary propulsion system (APS). The Space Shuttle OMS/RCS systems are considered state-of-the-art in flight-proven on-orbit propulsion technology. However, the next generation of launch vehicles will require higher performing, lighter weight and less complex systems than are in use today. Although not currently identified as a priority technology need by the user codes, it is anticipated that this technology will surface as a higher priority as the Agency draws nearer to new vehicle development.

The APS element would likely be composed of three subelements: (1) "hot rocket" technology as applied to orbital maneuvering and attitude control (OM/AC) systems using earth storable propellants (e.g. hydrazine/NTO, MMH/NTO); (2) "hot rocket" technology for OM/AC systems using space storable propellants (e.g. LOX/hydrocarbon); and (3) an

integrated oxygen/hydrogen APS which will utilize liquid orbital maneuvering and gaseous attitude control systems.

The "hot rocket" technology centers around thrust chamber materials than can withstand high temperatures. Current non-regeneratively cooled engines (e.g. attitude control) have temperature limited thrust chambers that can withstand combustion temperatures with only minimal fuel film cooling. The advantage of the integrated LOX/LH2 APS is the coupling of the attitude control system to the higher performing orbital maneuvering system using only one set of propellants.

4.3 Space Transportation

- 4.3.1 Overview
- 4.3.2 Advanced Cryogenic Engines
- 4.3.3 Nuclear Propulsion
 - 4.3.3.1 Nuclear Thermal Propulsion
 - 4.3.3.2 Nuclear Electric Propulsion
- 4.3.4 Aeroassist (Aerobraking)
- 4.3.5 Cryogenic Fluid Systems
- 4.3.6 Transfer Vehicle Structure & Cryogenic Tankage
- 4.3.7 Transfer Vehicle Avionics
- 4.3.8 Autonomous Landing
- 4.3.9 Autonomous Rendezvous & Landing

4.3.1 Overview

The term "Space Transportation" as used here refers to stages or vehicles for use in transportation within and beyond low Earth orbit, e.g., for transportation following delivery into low Earth orbit. This includes local movement of equipment within Earth orbits; it includes delivery of automated spacecraft to all regions for Solar System exploration; and it includes delivery of crews and equipment for human exploration of the Moon and Mars. The Space Transportation portions of the proposed technology programs are therefore to support improvements in current upper stages and / or development of new stages / vehicles for these applications. The objective of the Space Transportation area is to develop and validate technologies that enable high energy, high performance upper stages and cargo & personnel vehicles for Lunar and Mars missions.

Overall technology advances are needed to: extend our capabilities beyond those currently available; improve reliability, safety, performance and efficiencies of systems; and reduce support requirements and streamline operations where significant cost improvements could be realized.

Since everything that is used in space today must first be launched into space at considerable cost, there is an additional incentive for propulsion or related performance improvements to reduce or minimize the mass of space transportation systems. This results in emphasis on technologies that could allow safe and reliable use of performance-enhancing systems such as cryogenic engines, nuclear propulsion, or aerobraking.

Avionics technology advances are needed to support the avionics system which serves as brain and nerve system for these complex vehicles and missions, and to minimize equipment support requirements and software costs. The emerging field of "vehicle health

management" offers promise in this respect. Advances in structures and materials are needed for long-term exposures in the sometimes harsh environments in space, to allow vehicle weights to be reduced, and to allow manufacturing / maintenance at reduced costs. Some of the more ambitious missions will extend beyond our experience-to-date in space operations. Technology advances are needed to enable operations such as automated rendezvous & docking in space, in-space assembly and check-out of vehicles in preparation for exploration missions, and automated hazard avoidance and landing on the Moon or Mars.

These technology needs for each of the user vehicles / systems are shown in matrix format in Figure 4.3-1, and a summary of the key technologies to be pursued within each of the program elements shown in Figure 4.3-2, as a prelude to discussion of the individual technology program elements.

In the following discussions of individual technology elements, topics will be addressed in the following sequence, where applicable:

- Overview of element and proposed technology program.
- Current and related programs, including applicable parts of on-going Base R&T and Focused technology programs.
- Proposed technology program, and
- Summary discussion of technology benefits derivable from the technology capability and the proposed technology work.

Figure 4.3-1
User Vehicle Technology Requirements / Applications

Technology Element \ User Vehicle/ System	Upper Stages/ Impr's	Cargo Transfer Vehicle (CTV)	Space Transfer Vehicle (STV)	Lunar Transport. System (LTS)	Mars Transport. System (MTS)
• Advanced Cryo Engines	x		x	x	x
• Nuclear Thermal Prop.				Pot.	x
• Nuclear Electric Prop.	x*			Pot.	x
• Aeroassist (Aerobraking)	x		x	x	x
• Cryo Fluid Systems	x		x	x	x
• Veh Structures/Tanks	x	x	x	x	x
• Transfer Veh Avionics	x	x	x	x	x
• Autonomous Landing				x	x
• Auto Rendez/Docking		x	x	x	x

* may include upper stage solar powered option

**Figure 4.3-2
Space Transportation Technology Program Elements**

Advanced Cryogenic Engines: Main Engines: Compressor & Heat Transfer for Turbine Drive High Speed, Variable Flow Turbopumps Long Life Bearings & Seals Thrust Chamber Materials & Wall Design High Expansion Ratio Nozzles Integrated Control & Health Management Engine & System Handling / Support Equipment Nuclear Thermal Propulsion: Reactor Fuels Reactor Design / Heat Transfer Turbopumps Nozzles Reactor & System Ground Testing Nuclear Electric Propulsion: Reactor Power Source Power Conversion Electric Power Processing & Management Long Life Electric Thrusters High Temperature Heat Rejection Systems System Ground & (scaled) Flight Testing	Aeroshell (Aerobraking): AFE Data Assessment CFD Models Radiative Heating / Wake Models TPS Materials Validation Aerobrake GN&C Structural Test Bed / Aerobrake Assembly Flight Test Requirements (Mars Aerobrake) Cryogenic Fluid Systems: Liquid Storage Liquid Supply Liquid Transfer Fluid Handling Ground System Testing Flight Test Requirements (CONE & COHE) Transfer Vehicle Structures & Cryo Tankage: Characterization of Aluminum-Lithium & Composite Materials Cryotank and Vehicle Structure Applications Thermal Protection Systems Manufacturing Technologies for Component Fabrication Structural Design & Analysis Methods	Transfer Vehicle Avionics: Avionics Architectures Advanced Software Engineering Vehicle Health Management Advanced GN&C Electrical Actuator Systems Power Management & Control Autonomous Landing: Precision Landing Image / Map Matching Navigation On-Board Hazard Detection & Avoidance Sensors Algorithms Sensor & System Simulations Autonomous Rendezvous & Docking: Integrated GN&C Sensors & Sensor Data Processing Advanced Algorithms & Techniques Mechanisms & Effectors System Ground Testing
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4.3.2 Advanced Cryogenic Engines

Overview

The objective of the Advanced Cryogenic Engines Technology Program for space transportation vehicles is a high-performance, wide thrust range, multi-start LOX/LH₂ engine for upper stage and long duration in-space applications with minimal check-out and operations. The program will enable orbital transfer as well as travel to, landing upon and return from the Moon, Mars and other planets in the Solar System. It will also provide engine systems technology for upper stages (NLS, commercial). The high performance of cryogenic-fueled propulsion systems is strongly needed for these missions, along with high reliability for manned vehicles and operability over long-duration missions. The program focuses on technologies for operationally efficient, high performance, liquid oxygen-liquid hydrogen, expander cycle engines which may be operated and maintained in space. These advanced cryogenic engines will greatly enhance future missions (both manned and unmanned).

The Advanced Cryogenic Engines Technology Program will provide the technology necessary to confidently proceed with the development of moderate thrust liquid oxygen / liquid hydrogen, expander cycle engines for space transportation applications.

In those activities responding to space exploration, this technology program will provide advanced engines and propulsion systems to support automated spacecraft missions and for Lunar exploration missions. These same basic technologies will then be adapted for larger engines for use in Mars transfer and / or excursion vehicles.

Current & Related Programs:

Work has been underway for several years which has led to component technology advancements in the areas of high speed turbomachinery, high heat transfer combustors, large area ratio nozzles and engine health monitoring systems. Focused technology work

to build upon these basic technologies and to integrate them into engine systems has been initiated, and is currently on-going with limited funding. Analytical work, component-level technology work, and planning for engine system level test-beds are currently in progress; however, funding limitations have not allowed this work to proceed into the full scope. The work proposed in this Advanced Cryogenic Engines Technology Program will be an extension and expansion from current efforts, and with adequate funding will allow technologies for advanced engine systems to be developed and demonstrated.

While focused on advanced cryogenic engines, technology development in the Advanced Cryogenic Engines Technology Program encompasses technologies for the entire propulsion systems of future space transportation vehicles. As such, and to achieve the goal of operational efficiency in these future space vehicles, propulsion technology development efforts must be coordinated with related technology development efforts in the Transfer Vehicle Avionics, Structures & Cryogenic Tankage, Cryogenic Fluid Systems and Aeroassist areas. This program will continue close coordination with, and share applicable technology advances with, ETO vehicle propulsion technology developments.

Proposed Technology Program for Advanced Cryogenic Engines:

The major objectives of the Advanced Cryogenic Engines Technology Program include:

- (1) Identification and assessment of propulsion (engine and component) technology requirements;
- (2) Identification, creation, and/or validation of design and analysis methodologies/software, materials with required/desirable properties, and reliable, cost-effective manufacturing processes; and
- (3) Development and validation of engine subcomponent, component, subsystem, and system technologies focused on (in order of priority) reliability, operational efficiency, wide-range throttling, low cost manufacture, efficient performance, space environment durability, reusability/operation-environment durability and in-space maintainability.

The Lewis Research Center is the Lead Center with overall responsibility for the Space Chemical Engines Technology Program. The Marshall Space Flight Center participates with Lewis in several areas of the program. The program will be implemented in four integrated work elements: Propulsion Studies; Mission-Focused/Advanced Technologies; Mission-Focused/Advanced Components; and Engine System Technologies.

Propulsion Studies:

Major objectives include:

- Provide engine parametric data to support ongoing mission/vehicle studies.
- Identify and assess technology requirements of candidate propulsion systems.
- Optimize engine components and systems to satisfy propulsion system requirements.
- Identify issues and technologies related to efficient handling of engine hardware in space and ground environments.

Steady-state and transient models will be exercised to determine optimum component design points. Realistic requirements and specifications will be established for Integrated Controls & Health Management (ICHM) sub-system. Steady-state and transient models will be developed for initial configurations of Integrated Modular Engine (IME) concept, and for expander cycle engine at higher thrust levels (approx. 200,000 lb/Mars vehicle application). Operations efficiency issues will be defined and trade studies performed

toward optimization of space & ground based support hardware for propulsion system support.

Mission Focused/Advanced Technology:

The Mission Focused / Advanced Technology subelement will develop high payoff / high risk component and subsystem technologies for combustion devices and heat exchangers, turbomachinery, integrated control and health monitoring, valves / plumbing / interfaces, and efficient operations, utilizing laboratory, bench and rig testing.

Promising technologies will be incorporated into the design of components and propulsion subsystems which will be fabricated and tested as part of the Mission Focused / Advanced Components subelement.

Mission Focused / Advanced Components:

The Mission Focused / Advanced Components subelement will provide validated, advanced technology components for incorporation into propulsion system test-beds for system level validation testing.

Major objectives of the subelement include:

- Design, fabrication and testing of advanced technology components and subsystem approaches.
- Development of hardware demonstration units for operationally efficient approaches for space and/or ground-based support.
- Characterization testing of components individually in a component test facility, followed by incorporation into an engine system test-bed.
- Design and fabrication of operations support hardware, and demonstration utilizing mock-up and/or test-bed engine component hardware.

Engine Systems Technology:

This subelement provides for engine system level testing and demonstration of the individual components and technologies developed from the preceding sub-elements. This system-level testing will:

- Verify design and analyses for the basic high-performance, expander cycle components and engine system,
- Investigate system effects on component designs and interactions, control functions, and health management techniques,
- Characterize alternative components/technologies in an engine system environment, and
- Demonstrate operations support & engine handling hardware on an engine system.

Testing of components in engine systems test-bed configuration will verify analytical models and further define technology requirements for high performance, reliability, durability, and operations capability.

Technology Contributions to Vehicle Functions:

A summary re-cap of the technology element and subelement contributions to vehicle functions and vehicle related operations is shown in the following matrix. Six of these "functions" deal with operation of the vehicles; the other three deal with vehicle manufacturing, test and operations / support. As might be expected, the primary contributions of these technology efforts will be in improved operation of the engines / propulsion system and in allowing streamlined and lower cost operations. This is particularly true of the first six sub-elements, which are main engine related. Integrated Control & Health Management work will improve and reduce costs of engine maintenance / support, as well as enhance engine / controls operations. Technology efforts toward improved engine handling and support equipment will enhance ground and space operations.

ADVANCED CRYOGENIC ENGINES									
Technology Sub-Element	Functions								
	Sensing	Computing/ Data Process	Propulsion & Energy Conv	Aero Maneuvers	GN&C	Support Loads	Mfg.	Grd Test & Process	In-space Assy & Process
• Combustors			X				X	X	X
• High Speed Turbopumps			X				X	X	X
• Long Life Bearings/Seals			X				X	X	X
• Thrust Ch Matls/Design			X				X	X	X
• High Expansion Nozzles			X				X		
• ICHM	X	X						X	X
• Eng/Sys Handling/Suppt								X	X

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Technology Benefits Summary:

NASA's planning for future exploration of the Solar System includes unmanned (precursor) and manned missions to Mars and its moons, as well as resumption of manned missions to the Moon to establish Lunar observatories. A significant portion of the cost for these missions depends on launch vehicle and on-orbit fuel requirements. One of the keys to reducing cost is to minimize the propellant mass in low-Earth orbit required to achieve a transfer trajectory, to accomplish orbit insertion, to effect a planetary landing, and to return to Earth. Launch of the many millions of pounds required for virtually all future space exploration mission scenarios may be affordable only if advanced propulsion systems can be made available. Reduced propellant requirements in orbit translate to substantial cost savings because fewer Earth-to-orbit vehicle launches are required to accomplish the mission. A key enabling technology to greatly reduce in-orbit propellant mass requirements is the development of high-performance cryogenic rocket engines.

Another key to reduced cost is the development of reusable transfer stages that are: based in and operated from low-Earth orbit, operated in LEO to GEO space, and used in exploration missions. Technologies that will enable automated in-orbit operation (such as refueling, maintenance, servicing, and preflight systems checkout, as well as fault-tolerant in-flight operation) are critical to successful development and use of space-based vehicle systems. Integrated controls and health monitoring systems will be required for such fault-tolerant engines which will be repeatedly operated and maintained in space.

4.3.3 Nuclear Propulsion

Overview:

Use of nuclear energy as the power source for space vehicle propulsion has potential for use in several applications. Relatively small nuclear power sources may be

utilized for propulsion for automated spacecraft to explore outer reaches of the Solar System. Nuclear power units of much larger size are candidate propulsion approaches to propel either manned vehicles or associated cargo transports for human exploration of Mars and the Moon. Two forms of nuclear propulsion are being examined. In Nuclear Thermal Propulsion (NTP), energy from the nuclear source is used directly to heat and accelerate a working fluid (hydrogen), thereby producing thrust. In nuclear-electric propulsion (NEP), nuclear energy is used to produce electricity, which is in turn utilized to accelerate charged particles and producing low levels of thrust at very high specific impulse.

The approach for both NEP and NTP are similar and although the technologies being developed are related in some cases, they are very different in others. For both systems the approach will include conceptual design, enabling technology, innovative technology, safety and environmental considerations, public perception, and facility definition. Both NEP and NTP will be funded jointly by DOE and NASA and will be implemented by a team consisting of NASA Centers (MSFC, JPL, LeRC, JSC, etc.) and DOE National Laboratories (INEL, LANL). The Level II Project Office will be located at NASA Lewis Research Center and this office will be tasked with the overall planning, system concept design, technology development, facilities, safety, etc. The Nuclear Propulsion Office (NPO) will be jointly staffed by NASA and DOE. The technology development will be conducted by a team consisting of NASA Centers, National Laboratories, Industry and Academia.

4.3.3.1 Nuclear Thermal Propulsion

The objective of the Nuclear Thermal Propulsion element is to develop nuclear propulsion technologies capable of fulfilling requirements such as performance, long life, and multiple starts for future piloted, cargo and robotic precursor missions to and from Mars and the Moon.

SEI requirements will drive definition of candidate nuclear propulsion concepts, and these concepts will direct the enabling technology. Reference propulsion system designs will be developed early in the project to define the component and subsystem configurations, to permit development of system technologies for nuclear propulsion, and to permit the selection of a propulsion system for further development that will satisfy the requirements for Moon and Mars cargo and piloted missions.

Current & Related Programs:

The nuclear thermal propulsion technology program will build upon the considerable base of developments as part of the "NERVA" nuclear rocket program in the 1960s/70s. Current state-of-art, as a starting point for the proposed program, includes:

- Reactor Fuels:
 - Full system testing to 2 350 degrees K (825 sec I_{sp}) for full operating life and multiple cycles was completed in NERVA/ROVER program (CIRCA 1970)
 - Nuclear furnace tests were completed of composite fuels to peak temperatures of 2450 degrees (2750 degrees K in electric furnace tests) (circa 1972)
 - Binary carbide, ternary carbide fuels (2700-3100 degrees K) have been proposed, but not verified
 - Other advanced fuels (3300-3500 degrees K) are proposed, but not verified

- Nozzles:
 - Nozzle technology has improved significantly compared to NERVA design. (e.g., SSME can accommodate exhaust temperatures >3100 degrees K and nozzle heat fluxes 4 times greater than in NERVA).
 - Uncooled carbon composite nozzle skirts are used on smaller nozzle applications. Much engineering/validation is required for sizes proposed
- Turbopumps:
 - 3000-7000 PSI SSME turbopump represent the SOA for turbopump technology. Composite rotor components have been proposed, but not validated
- Reactor Design/Heat Transfer:
 - Several concepts have been proposed; feasibility issues remain with some of the advanced concepts
- Safety, Autonomous Operation:
 - Instrumental/control, AI, and health monitoring systems must be developed.

Planning efforts have been in place since Spring 1991 to define candidate system and the enabling technologies required to meet performance goals. The planning effort has been a joint effort with NASA Headquarters, DOE Headquarters, NASA Centers, and DOE National Laboratories.

Proposed Technology Program for Nuclear Thermal Propulsion:

The primary mission requirement for a nuclear thermal propulsion system is the piloted Mars mission. The primary system performance requirements are a specific impulse between 825 and 1050 sec., restart capability, 3 - 5 hours of operating time and man-rating. These system requirements translate into technical challenges such as:

- Systems designs
- Fuel temperature 2700 - 3100 degrees K
- Fuel lifetime in hot hydrogen environment 3 - 5 hours.
- Facility for full system ground testing.
- State-of-the-art autonomous/robotic operations.
- Man-rating.
- High temperature materials.

Technologies for Nuclear Thermal Propulsion will be developed through technology readiness level #6 (full system ground testing). Some of the key schedule milestones for NTR are:

- Lab-scale demonstration of 2700 degrees K reactor fuel.
- Complete conceptual designs of selected concepts for piloted Mars mission.
- Nuclear furnace facility complete.
- Select NTR concept(s) for system testing.
- Systems facility construction complete.
- First NTR reactor test complete.
- Full system ground testing complete verifying technology readiness level 6.

Technology Contributions to Vehicle Functions:

A summary re-cap of the technology element and subelement contributions to

vehicle functions and vehicle related operations is shown in the following matrix. At this stage, most of the technology efforts are devoted to testing and proving out the basic elements of the nuclear power source and conversion of that energy into production of thrust. Later work will deal more directly with operation, maintenance and support of the nuclear powered propulsion systems.

NUCLEAR THERMAL PROPULSION									
Technology Sub-Element	Functions								
	Sensing	Computing/ Data Process	Propulsion & Energy Conv	Aero Maneuvers	GN&C	Support Loads	Mfg.	Grd Test & Process	In-space Assy & Process
<ul style="list-style-type: none"> • Reactor Fuels • Reactor Design/Heat Xler • Turbopumps • Nozzles • Reactor & Sys Grd Testing 			<ul style="list-style-type: none"> X X X X X 				<ul style="list-style-type: none"> X X 	X	X

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Technology Benefits Summary:

Nuclear thermal rockets offer a possibility for a combination of high thrust and high propulsion efficiency (high specific impulse). For piloted missions to Mars, this propulsion efficiency provides a possibility for reduced transit times, and / or reductions in transfer vehicle masses and ETO launch requirements. Reductions in Mars mission transit times may have particular significance for crew exposure to radiation or other deep-space environmental factors, and would obviously reduce life support and mission support requirements. This superior performance of nuclear rockets would also pay off for piloted and cargo Lunar missions, Mars cargo missions and robotic planetary missions.

4.3.3.2 Nuclear Electric Propulsion

The objective of the Nuclear Electric Propulsion program is to develop a high I_{sp} option which could enable far planetary missions with expanded science capabilities and expand exploration mission options. It has potential for application in automated spacecraft delivery, for cargo delivery in conjunction with human exploration missions (including "slow freight" delivery), and for piloted Mars missions.

NEP lends itself to a range of space mission applications and an evolutionary system growth path. Mission performance requirements for several of these mission applications follow:

- For interplanetary applications, total electrical power level (P_e) from .1 to 1 MW_e , power/propulsion system specific mass (α) from 30 to 50 kg/ kW_e and lifetime from 10 to 12 years are required.
- For lunar and Mars cargo applications, P_e from .5 to 10 MW_e , α from 10 to 20 kg/ kW_e and lifetime from 3 to 10 years are required.
- For Mars piloted applications, P_e from 5 to 60 MW_e , α from 1 to 20 kg/ KW_e and lifetime from 3 to 10 years are required.

Current & Related Programs:

The technology program of focused work toward nuclear-electric propulsion capabilities will complement and build upon related technology work in several areas, including the following:

Space Nuclear Power:

- DOE MWe Program
- DOD/DOE/NASA /SP-100 Program - 100 kW_e

Electric Propulsion:

- NASA OAET base R&T in electric propulsion - ARCJET, ION, MPD Thrusters
- Air Force Electric Propulsion Program - ARCJET, MPD Thrusters, SEP Flight Tests
- International :
 - USSR (MPD, closed Drift Hall Thrusters)
 - Japan (ION, MPD Thrusters)
 - ESA (ARCJET, ION, MPD Thrusters)

Proposed Technology Program for Nuclear Electric Propulsion:

The approach for Nuclear Electric Propulsion technology development will include conceptual design, enabling technology, innovative technology, safety and environmental considerations, public perception, and facility definition. NEP will be taken through technology readiness level # 5 (subsystem ground testing), but not a full up system ground test.

For NEP, full system application for a Code S planetary robotic science mission is being investigated. Both NEP and NTP will be funded jointly by DOE and NASA and will be implemented by a team consisting of NASA Centers (MSFC, JPL, LeRC, JSC, etc.) and DOE National Laboratories (INEL, LANL, ORNL, SNL, etc.). The Level II Project Office will be located at NASA Lewis Research Center and this office will be tasked with the overall planning, system concept design, technology development, facilities, safety, etc. The NPO will be jointly staffed by NASA and DOE. The technology development will be conducted by a team consisting of NASA Centers, National Laboratories, Industry and Academia.

Key technologies for NEP include lightweight, reliable, high power nuclear heat source and power conversion, efficient, long lived electric thrusters, low mass, high temperature heat rejection systems and high temperature power management, and distribution systems. These key technologies will be developed under the NEP technology program, applying imminent technologies to nearer term, low power applications, and advanced technologies to progressively more demanding applications. Enabling technology programs applicable to NEP are already in existence, such as SP-100, electric thruster base R&T, and the Civil Space Technology Initiative (power conversion and thermal management technology). Such programs do provide technology leverage for NEP, not only providing a significant portion of the required technology for the low power mission applications, but representing a strong starting point for the technology program needed for the more demanding mission applications.

Some of the key milestones for NEP are:

- Complete 400 kw electric propulsion testing facility and designs for high power (MW class) electric thrusters.

Complete candidate systems study for reactor power source, power conversion, power processing, thruster and control concepts.
 Complete breadboard demo of megawatt class electric thruster technology
 Verify 100 hours of life for 500 kW electric propulsion system.
 Complete ground tests to verify megawatt class power/propulsion system
 Verify TRL-6 through flight test of 500 kW subscale NEP vehicle.

Technology Contributions to Vehicle Functions:

A summary re-cap of the technology element and subelement contributions to vehicle functions and vehicle related operations is shown in the following matrix. Again, most of the early technology efforts are aimed toward testing and proving out basic operations of the nuclear power source, equipment to produce electric power, and the electric thrusters. Later efforts can concentrate more on maintenance and support for the propulsion systems.

NUCLEAR ELECTRIC PROPULSION									
Technology Sub-Element	Functions								
	Sensing	Computing/ Data Process	Propulsion & Energy Conv	Aero Maneuvers	GN&C	Support Loads	Mg.	Grd Test & Process	In-space Assy & Process
• Reactor Power Source			X						
• Powerconversion			X						
• Power Processing			X						
• Long Life Electr Thrusters			X						X
• High-temp Heat Rej Sys			X						
• Grd & Flight Testing			X						

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Technology Benefits Summary:

Use of nuclear power to drive electric thrusters (with very high fuel efficiency but very low thrust levels) may prove highly attractive for delivery of automated spacecraft to outer reaches of the solar system, for cargo delivery to the planet Mars in conjunction with human exploration missions ("slow freight delivery"), and possibly for powering the manned Mars ships, themselves. NEP's very high propulsion efficiency (high specific impulse) would greatly reduce propellant mass requirements, and would significantly improve mission flexibility. Changes in mission objectives and year-to-year variations in energy requirements for planetary exploration missions could be more easily accommodated than with lower performing chemical rocket propulsion. This technology program will explore and demonstrate capabilities of nuclear electric propulsion for these applications.

4.3.4 Aeroassist (Aerobraking)

Overview:

The terms "Aeroassist" or "Aerobraking" refer to use of atmospheric drag to decelerate a space vehicle, and is employed to avoid the large mass requirements for propulsive deceleration. A form of aeroassist has been employed routinely in re-entry of Apollo spacecraft and the Space Shuttle Orbiter. These terms as used in discussion of this technology program will include: (1) capture into a planetary orbit, (2) reduction of orbit altitude, (3) direct entry from a hyperbolic trajectory, and (4) entry from orbit. The

objective of the aeroassist technology element is to provide substantial reduction in mass or increased payload for atmospheric capture missions.

The Aeroassist (Aerobraking) program element is focused on developing technologies for manned Lunar missions, robotic and manned Mars missions, and planetary exploration robotic missions. This is a multidisciplinary, multi-Center program with key technology issues in aerothermodynamics, thermal protection materials, GN&C and structures. A strong technology integration effort is also needed to balance the needs of missions, system design, and system operations with technology requirements and to make tradeoffs between disciplines. Technology products are planned to meet the technical and schedule needs of the various types of missions.

Direct entry from Lunar missions has been demonstrated in the Apollo program. Manned Lunar aerobrakes (aerobrakes for capture into Earth orbit upon return from Lunar missions), which are near the current state-of-the-art, do require modest extension and validation of current capabilities as well as significant advancement in in-space operations. Technology programs focus on validation of CFD modeling for radiative heating and wake flow and on validation of STS TPS derivative materials. The Aeroassist Flight Experiment will provide a flight validation of these key technologies in an environment which is near to that for Lunar return flight. The operational aspects of assembly and deployment provide present challenges for structures technologies which may also require flight validation. In addition, the Lunar aerobrake provides a foundation for the more challenging Mars missions.

Manned Mars missions of shorter trip times extend critical aerobraking flight environments well beyond the level of the Lunar aerobrake for both Mars capture and the return to Earth. Because of the challenging technology requirements as well as the later need date, this portion of the technology program will focus on technology development prior to the validation phase of the program. Mars aerobrake configuration requirements are challenged by the complex interaction of mission design, human factors, technology capabilities, and vehicle design. CFD modeling requires further extension into regions where radiative heating can be the dominant phenomenon. TPS materials must withstand temperatures well beyond STS type material capabilities, and guidance systems must efficiently cope with a Martian atmosphere which is highly variable. And, operational aspects of assembly and deployment are even more challenging for a Mars aerobrake shell, which would be twice the diameter of a Lunar aerobrake. Because of the large difference between the Lunar and Mars environments and the level of technology requirements, a flight test experiment / demonstration based on the Mars mission is planned; this proposed flight experiment is discussed in Section 4.4 of this report.

Current & Related Programs:

Aerothermodynamics R&T Base provides a unique resource for defining the aerodynamic characteristics and the aerothermal loads encountered by aeroassist vehicles; that is, a mission-enabling technology for exploration. This resource evolves from the research devoted to the development of both "benchmark" and "engineering" computational tools and the research associated with land and flight experiments that provide the data bases for modeling important physical phenomena, and for calibrating / validating the computational tools. Advancements in this element are essential to the performance of future aeroassist missions. Improved physical modeling and calibrated computational tools can produce significant reductions in design margins, higher performance and reduced life-cycle costs.

The Aeroassist technology program will depend upon, and will build upon, data to be

gained from the Aeroassist Flight Experiment; and will include as a primary element a High Energy Aerobrake (for Mars aerobrake conditions). Both of these flight experiments are discussed in section 4.4. The Aeroassist technology program will also require collaboration with GN&C developments as part of Space Transfer Avionics technology element; with high temperature structures / TPS work under the Space Transfer Structures / Tankage technology element; and aerobrake assembly / deployment work to be performed as part of In-Space Vehicle Assembly work (in Operations technology program).

A focused technology program to develop aeroassist technologies was initiated as part of the Pathfinder program, but with very limited funding. Fiscal year 1991 was intended to be a growth year for the Aeroassist Program. Instead it was a survival year. The current program ends in FY91; with a transfer of funds, the program could, however, maintain another survival year. The FY91 strategy is to keep the established inter-center team together, consolidate key activities (by reducing the number of center participants, deferring test/validation activity, and not entering new areas), and to focus on defining technology requirement, in terms of system refinements and supporting analyses. The proposed program will be implemented as an extension and expansion of this current program.

This proposed inter-center program has been derived from the existing Aerobraking Technology Project Plan of the Exploration Technology Program and from the previous High Energy Aerobraking Project Plan developed under Project Pathfinder. Modifications have been made to these previous plans to reflect changes in mission characteristics and schedules.

Proposed Technology Program for Aeroassist (Aerobraking) :

The objective of the Aerobraking Technology project is to develop and validate key supporting technologies which allow the effective use of aerobraking for manned lunar missions, robotic and manned round trip missions to Mars, and other planetary exploration missions. The term Aerobraking in this context includes (1) capture into a planetary orbit, (2) reduction of orbit altitude, (3) direct entry from a hyperbolic trajectory, and (4) entry from orbit.

The Aerobraking technology project supports the full range of requirements for Mars, Earth, and Planetary Aerobraking,

- Lunar Aerobrake for Manned Missions
 - Forebody and wake CFD models
 - Reusable thermal protection materials validation
 - Structural test bed for assembly
 - AFE Assessment
- Mars Mission Aerobrakes for Mars and Earth Aerocapture
 - L/D configuration/entry velocity requirements
 - Radiative heating/wake models
 - Adaptive guidance & control, optical navigation
 - High temperature ablator TPS
 - Lightweight aeroshell assembly
 - Flight test requirements
- Robotic Planetary/Sample Return Aerobrakes
 - CFD Models
 - TPS materials validation

The key supporting technologies include aerothermodynamic modeling; high temperature thermal protection systems; adaptive guidance, navigation, and control; and light weight structures using in-space construction and/or assembly. Aerobraking systems are strongly affected by each of these supporting technologies. System analysis which addresses missions, vehicle concepts, and operations is used to integrate across the discipline areas, to assess technology requirements and trades, and to assure system requirements are satisfied. Aeroassist Flight Experiment results will be assessed and requirements for post-AFE flight experiments will be defined.

Aerobraking Technology Requirements (chronological order, top to bottom):

<u>Development</u>	<u>Validation</u>	<u>Flight Test</u>	<u>Readiness</u>
Mars Capture	Lunar	AFE	Mars Network Probes
Mars-Earth Return	Robotic	Prep	Small Planet Probes
	MRSR		Ground based Lunar
Mars Capture	MRSR	AFE	MRSR
Mars-Earth	Growth Lunar	Assessment	Space based lunar
Return		AFE II	(aerobrake)
		Develop	Comet Sample
			Return
Growth Mars	Mars Capture	AFE II Results	Mars Extended
	Earth Return		Rovers
	Mars Entry		Mars Capture
			Mars Entry
			Earth Return

Critical Technology Activities:

Mars entry probes code validation
 AFE flight data code/TPS assessment MRSR aerocapture validation
 Lunar LTV Codes, TPS, Assembly validated Comet sample return
 Codes, TPS validated
 AFE II (High energy / Mars) flight test
 Mars mission validation Codes, GN&C, TPS, Structures

Technology Contributions to Vehicle Functions:

A summary re-cap of the technology element and subelement contributions to vehicle functions and vehicle related operations is shown in the following matrix. Contributions of aeroassist technology efforts will contribute in proving out approaches for basic functions of the aerobrake, plus the very key area of techniques for assembly / deployment of large-diameter aerobrakes in space. Technology efforts to support Lunar aerobrakes will concentrate on adaptation of data / experience from the Aeroassist Flight Experiment, and aerobrake assembly / deployment of techniques. Technology efforts aimed toward the much more challenging Mars aerobrakes will concentrate in addition on basic aerothermodynamics and thermal protection materials / systems.

AEROASSIST (AEROBRAKING)

Technology Sub-Element	Functions								
	Sensing	Computing/ Data Process	Propulsion & Energy Conv	Aero Maneuvers	GN&C	Support Loads	Mfg.	Grd Test & Process	In-space Assy & Process
<ul style="list-style-type: none"> • AFE Data Assessment • CFD Models • Heating/Wake Models • Tps Materials • Aerobrake GN&C • Struct Testbed & AB Assu • Fit Test Rqmts 				<ul style="list-style-type: none"> X X X X 	X				X

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Technology Benefits Summary

Use of aeroassist or aerobraking to decelerate a space vehicle for landing or for capture into a planetary orbit can avoid the substantial weight penalties, compared with performing all maneuvers propulsively. This savings is particularly important for capture at a target planet or in Earth return from Lunar / Mars missions, because propellants for these maneuvers would first have to be transported out to the target planet, or out there and back. The total mass of manned Mars round-trip missions might stretch practical limits, if all-propulsive and conventional chemical rocket propulsion were used. A principal part of this benefit is a reduction in the ETO launch / mass requirements. For these benefits to be realized, it will obviously be necessary that the weight of the aerobrakes themselves do not become large enough to off-set the propulsion mass reductions. This is one of the challenges for the Aeroassist and Structures technologies elements.

4.3.5 Cryogenic Fluid Systems

Overview:

The goal of the NASA Cryogenic Fluid Systems (CFS) technology development program is to develop the focused technology required to efficiently, effectively, and safely utilize subcritical cryogenic liquids in the low-gravity environment of space.

The overall objective of the CFS element is to provide the technology necessary to reduce cost and performance penalties associated with cryogenic hydrogen systems, particularly long-duration space missions. Program objectives include: (1) identification of the focused technologies required for the design of in-space cryogenic fluid systems, (2) assessment of the present state of readiness of the identified technologies, (3) determination of the technology readiness goals, (4) perform the necessary research and development activities to meet the readiness goals, and (5) create a design data base for incorporating the technology development activities into the design of cryogenic fluid systems.

There are four sub-elements in the CFS technology program: liquid storage, liquid supply, liquid transfer, and fluid handling. These technologies are enhancing or enabling to Space Transportation Systems for SEI. In addition, the majority of key future missions other than SEI can not be performed efficiently without significant improvements in the state-of-the-art in all these sub-elements.

With the exception of thermal and pressure control for missions on the order of a few hours or instrument coolers using small amounts of cryogens, a subcritical cryogenic fluid storage capability does not exist. The key objective of liquid storage technology development is in the capability of storing large quantities of subcritical cryogenic fluids for

mission durations of one month to three years and the optimization of the trade between tank boil off losses and storage tank thermal control system mass.

The acquisition of a single-phase, subcritical cryogenic liquid has never been demonstrated in a low-gravity environment. For large or logistically complex systems, propulsive settling techniques will not be viable. Therefore, this technology development will establish methods of acquiring, retaining, and pressurizing/pumping liquids from a cryogenic supply system under low-gravity conditions.

An on-orbit liquid-transfer capability does not currently exist; most of the techniques associated with these technologies have been performed only recently in ground-based test facilities. The objective in this subelement is to be able to perform a complete on-orbit liquid transfer to a typical spacecraft (e.g., a Space Transfer Vehicle) yielding tanks at least 95 percent full during one astronaut shift (approximately eight hours) while maintaining propellant tank pressures below approximately two atmospheres without venting.

Likewise, the development of cryogenic fluid handling technology presents many challenges. As the mass fraction increases for large space systems, the fluid slosh control problems increase, particularly during docking/mating operations. In man-rated systems, the issues of tank venting and dumping become safety critical, as well as performance enhancing. Likewise, advanced instrumentation, such as low-g mass gauges and leak detectors, is mission critical, especially to support "Go/No Go" decision points.

Current & Related Programs

The joint LeRC and MSFC CFS technology development program for the four CFS sub-elements has been defined through fiscal year 2005 in order to meet the technology development needs of future missions in a timely manner. LeRC will serve as the Lead Center with MSFC acting in a Participating Center role for CFS technology.

In the liquid storage subelement, the program addresses both thermal control and pressure control subtasks. In the thermal control subtask, LeRC is concentrating on thick, purged MLI, and MSFC is focusing on foam/MLI. In the pressure control subtask, LeRC builds and maintains a technical database for a range of tank geometries, conditions, and fluids. MSFC focuses on future vehicle applications and system-level integration with other CFS subsystem/elements.

The liquid supply subelement contains two subtasks, liquid acquisition and pressurization. The MSFC focus is on ground and storable fluid flight experiments and partial acquisition devices (e.g., start basket or other LADs related to engine/stage application) and includes a project to conduct experimental evaluation of rapid pressurization (with ullage positioning) for a wide variety of space vehicles. The LeRC focus is on two pressurization projects that involve experimental evaluation of slow pressurization (without ullage positioning) for resupply tanker/depot issues.

The liquid transfer subelement contains several subtasks. LeRC is concentrating on zero-g no-vent fill technology development and is compiling a technical database for a range of tank geometries, inlet conditions, and fluids. MSFC is concentrating on technology development applications to a wide variety of space vehicle CFS subsystems/elements.

There are three subtasks in the fluid handling subelement (i.e. venting/dumping, fluid dynamics, and advanced instrumentation/components). LeRC and MSFC have identified 17 projects to cover these sub-tasks. LeRC is focused on 12 projects investigating fluid dumping and slosh behavior, while MSFC is focused on three projects centering on quick

disconnects. LeRC and MSFC participate jointly in two projects to develop cryogenic pumps and valves.

To ensure that the CFS technology program meets the needs of future missions, systems integration studies and cost/benefit analyses are underway. For each technology, an analytical model will be developed and/or validated to enable performance predictions of future cryogenic fluid systems. Large-scale and/or system-level, ground-based tests will be conducted for those technologies where 1-g data are meaningful. For technologies where low-g data must be obtained to provide analytical model validation, space experiments, such as the Cryogenic Orbital Nitrogen Experiment and the Cryogenic Orbital Hydrogen Experiment, will be advocated (See section 4.4). The focused CFS technology program will be coordinated closely with the CONE and COHE elements of the focused Transportation Technology Program and the Cryogenic Fluid Management and IN-STEP Base R&T programs

In addition to the common utilization of cryogenic fluids as vehicle propellants, they are also likely to be utilized for energy storage on the surface of the Moon and/or Mars to support manned habitats, surface exploration, in situ resource development, etc. Similar applications would apply to surface rovers. Other applications of cryogenic fluids include liquid hydrogen as a reactant for nuclear thermal propulsion and liquid oxygen and liquid nitrogen for life support. Efforts will be made to provide synergy with other program elements that use or will use cryogenic fluids.

Limitations in our capabilities to operate cryogenic systems in space for extended periods have been recognized for some time. The joint program, as discussed in this section, is considered to be well rounded and has come as a result of considerable interaction, review, and planning by both LeRC and MSFC. Ground-based programs and flight experiments have been proposed, but not funded to date at levels to allow significant progress. In fact, current budgets (FY91, 92) are jeopardizing the ability to maintain a limited ground program and retain the personnel resources with experience in cryogenic fluid technology. The joint program, with adequate funding, will allow the technology capabilities necessary to NASA's future space program to be developed and demonstrated on a reasonable timetable. Without approval of this program and its funding, including the base Technology and flight experiments efforts, NASA's capability to design cryogenic flight systems for future missions will be limited and operations cost will be severely penalized.

Proposed Technology Program for Cryogenic Fluid System:

The program defined above is expanded here to include milestones through fiscal year 2005. The near-term (five years) technology program for CFS involves a major, joint ground testing program in the four CFS sub-elements. No milestones are shown for FY92 reflective of the zeroing out of the CFS budget for FY92.

Near-term ('91 -'96) LeRC and MSFC objectives and milestones for the liquid storage subelement include:

- Characterization of MLI for Lunar thermal conditions.
- Completion of tank self-pressurization tests.
- Data available for passive TVS model 1-g validation.
- Characterization of MLI for Lunar environmental conditions.

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- Completion of foam/MLI design database (Lunar applications).
- Demonstration of STV/LTV insulation system.
 - Servicing facility design criteria established.

Near-term LeRC and MSFC objectives and milestones for the liquid supply subelement include:

- Initial 1-g autogenous pressurization data provided.
- Final 1-g autogenous pressurization data provided.
- Propulsion stage subsystem demonstration completed.
- 1-g supply system demonstration completed.
- Propulsion integrated system performance.

Near-term LeRC and MSFC objectives and milestones for the liquid transfer subelement include:

- 1-g data available for high-flow rate transfer.
- Preliminary propulsion stage demonstration.

Near-term LeRC and MSFC objectives and milestones for the fluid supply subelement include:

- Version 2 - fluid dumping model completed.
- 3-D slosh model completed.
- 1-g LN₂ fluid dumping completed.
- Disconnect technology delivered.
- 3-D slosh model validation for zero-g.
- Pump/valve development completed.

The CFS technology development element (if funded at appropriate levels) will be complete by 2005 if the current joint LeRC/MSFC program is realized. The long-term (1997-2005) goals and objectives of CFS technology development include:

- Thick MLI generic model validation.
- LN₂ fluid handling component availability.
- Mars insulation performance demonstration.
- LH₂ fluid handling components availability.
- Health monitoring systems demonstration

Technology Contributions to Vehicle Functions:

A summary re-cap of the technology element and subelement contributions to vehicle functions and vehicle related operations is shown in the following matrix. Contributions of CFS technology efforts will be primarily in the two key areas as shown. One is to develop / demonstrate features for proper and efficient operations of the

cyrogenic-fueled propulsion systems and associated storage / feed systems, and the second is to enhance vehicle support operations in space. Both include long-term storage of fluids at cryogenic temperatures with minimum boil-off losses, and the ability to acquire and transfer cryogenic propellants under zero-low gravity conditions.

CRYOGENIC FLUID SYSTEMS									
Technology Sub-Element	Functions								
	Sensing	Computing/ Data Process	Propulsion & Energy Conv	Aero Maneuvers	GN&C	Support Loads	Mfg.	Grd Test & Process	In-space Assy & Process
• Liquid Storage			X						X
• Liquid Supply			X						X
• Liquid Transfer			X						X
• Fluid Handling			X						X
• Grd System Testing			X						X
• Fit Test Rqmts			X						

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Technology Benefits Summary:

When compared to Lunar mission scenarios utilizing state-of-the-art CFS technology, Lunar mission concepts based on advanced CFS technology are safer and cost substantially less. Reusable space transfer vehicle concepts employing advanced CFS technology could save more than \$10 billion in life cycle costs during the Lunar initiative. Concrete examples of the types of savings possible with advanced CFS technology depend upon the scope, goals, and number of missions in the Lunar initiative. Advanced MLI technology could save from \$7 million to \$45 million per mission in reduced boil off losses/reserves. Advanced zero-g tank pressure control technology could save from \$5 million to \$314 million per mission through RCS propellant requirement reductions. Advanced zero-g mass gaging technology could save \$18 million per mission in fluid reserves. In mission architectures that would utilize both advanced zero-g cryogenic transfer technology and zero-g liquid acquisition device technology, savings of \$418 million to \$835 million per mission could be achieved in Earth-to-orbit launch costs.

The LeRC/MSFC CFS program will deliver the needed level of CFS technology development required for all SEI architectures in less than 20 years. The development of this technology is closed-ended. The benefits in mission costs and mission safety from advanced CFS technology are quantifiable; they would continue to accrue through each SEI mission to the Moon and Mars. Additional benefits derived from this technology come from the array of possibilities it will foster for the utilization of space; all long-term space missions or space habitats will benefit greatly from advanced CFS technology.

4.3.6 Transfer Vehicle Structures & Cryogenic Tankage

Overview:

The objective of the Transfer Vehicle Structures & Cryogenic Tankage element is to develop low-mass, space durable materials required for safe, cost-effective missions. Most of our cryogenic vehicle experience to date has been in missions of a few hours in duration. The new generation of upper stages and transfer vehicles will be required to operate in space for weeks, months, or years; and may be based / maintained in space between missions. In addition to the natural environments of space, environments for vehicle structures range from deep cryogenic propellant temperatures to very high temperatures associated with aerobraking in Earth / planetary atmospheres. In addition, there is considerable incentive for any practical steps to minimize inert weight of in-space (to reduce

vehicle masses and ETO launch requirements). This technology program will allow systematic examinations and testing of candidate structural materials and design approaches for these conditions, and will allow development of low-cost manufacturing and maintenance approaches.

These technology developments will directly benefit any upper stage improvements or new developments, and will be required for space transfer / excursion vehicles.

Current & Related Programs:

There is considerable commonality between this structures / tankage technology element and the ETO structures / materials technology element. Work under these two elements will be performed with close and continuing collaboration. This technology work will also require close coordination with Cryogenic Fluid Systems element and the Aeroassist (Aerobraking) element.

Proposed Transfer Vehicle Structures / Cryogenic Tankage Technology Program:

Vehicle Structures and Cryotank program aims to develop and validate a technology base which will provide for weight and cost savings of 20-40 percent compared to conventional technology for fabricating cryotank and vehicle structures for space transportation systems. Weight savings will be achieved through the use of advanced materials and efficient design. Cost savings will result from the use of advanced fabrication methods coupled with lighter weight for reduced systems costs. Key supporting technologies include the characterization of Al-Li alloys and composite materials for lightweight cryotank and the associated manufacturing technology for component fabrication. Other supporting technologies include but are not limited to: development and verification of structural design and analysis methods, cryogenic insulation, thermal protection systems, for space transportation systems.

Technology Contributions to Vehicle Functions:

A summary re-cap of the technology element and subelement contributions to vehicle functions and vehicle related operations is shown in the following matrix. As noted in the matrix, contributions of these technology efforts will be in three key areas. The first is in efficient and low weight structures / tankage under long-duration exposures to space environments. The second area is to provide for low-cost manufacturing methods. And, the third is to enhance maintenance and support of structures / tankage in space during long duration missions, and potentially during space-basing between missions.

STRUCTURES & CRYO TANKAGE									
Technology Sub-Element	Functions								
	Sensing	Computing/ Data Process	Propulsion & Energy Conv	Aero Maneuvers	GN&C	Support Loads	Mfg.	Grd Test & Process	In-space Assy & Process
<ul style="list-style-type: none"> • Al-Li & Composites • Cryotank & Str Applic's • Thermal Protect Sys • Manufacturing Techn's • Struct Des & Anal Methods 						<ul style="list-style-type: none"> X X X X 	<ul style="list-style-type: none"> X X X 		<ul style="list-style-type: none"> X X X

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Technology Benefits Summary:

- Major weight savings, 20% to 40%, possible with advanced materials. One-for-one tradeoff of weight saved vs. payload.
- Cost reduction of 25% or more with low-cost manufacturing and automated production and inspection methods.

4.3.7 Transfer Vehicle Avionics

Overview:

The overall objective of the Transfer Vehicle Avionics technology development program is to provide the capability to develop self-contained avionics systems for long duration Mars missions where ground support systems are not readily available. The goals are to: 1) build on the foundation provided by similar work for the ETO Transportation, 2) provide the capability to develop self contained transportation systems for long duration Mars missions where ground support systems are not readily available, and 3) advance technologies in vehicle avionics architecture, software, health management, GN&C, electrical actuators, and power management and control for both short and long duration missions. These technologies are intended to improve efficiency and safety, (reliability, robustness, failure tolerance), decrease crew workload, and reduce cost of production / operation in the new generation of Space Transportation Systems and enhance the currently existing vehicles. Since Transfer Vehicle Avionics and ETO Avionics Technology development share common goals in several areas, this invites collaboration and interfacing between the two areas of development; however, a major technology challenge arises in the development of self contained space transportation systems necessary to operate without logistic supply lines, for protracted periods of dormancy, for long term exposures to charged particle / radiation and changing environment expected of the interplanetary space and planet surfaces.

Current & Related Programs:

There is no current avionics focused technology program in the Space Transportation area. Related programs will be discussed in the context of the proposed technology program.

Proposed Technology Program for Avionics:

The Transfer Vehicle Avionics Technology Program contains the subelements of Avionics Architecture, Advanced Avionics Software, Vehicle Health Management, Advanced GN&C, Electrical Actuator Systems, Power Management and Control. All of these elements for Transfer Vehicles are closely related and inextricably linked one to the other through the systems engineering process. Thus, Vehicle Health Management should be addressed as part of the architectures and software elements that will support it. The basic system engineering discipline that considers the entire vehicle/system life cycle from inception to obsolescence is the thread that ties these elements into a cohesive package.

The ultimate goal of advanced Avionics Architecture development is an avionics architecture which is modular and maximizes the possibility of reuse of the architecture and components thus reducing development time and operations costs. It produces requirements which can drive the overall systems architecture; develops the architecture for each discipline area of avionics; identifies candidate standard(s) which support the

architecture; identifies critical areas within the architecture which require significant technology development; implements architecture evaluation in test beds within NASA and Industry to prove out the concepts. This will be tested through development of advanced simulation test beds for performance appraisals of new architecture design. The approach to development of Avionics Architecture currently includes the utilization of the Strategic Avionics Technology Working Group.

Architectures must support the development, access and maintenance of extremely large vehicle parameter databases that will support functions such as trend analysis and incipient fault prediction. Since long duration vehicles, manned and unmanned, are likely to rely on embedded simulations to perform tasks such as crew training, vehicle configuration monitoring & management, and health & status assessment, architectures must be developed that facilitate embedded simulations. This includes methods ensuring that simulated operations cannot inadvertently mingle with real-time flight operations and providing the connectivity (in terms of command and data streams) required by such simulations.

The Advanced Avionics Software subelement will address the mission and safety features in the software operation system kernel and in the run-time layers that surround it (including the networking that interfaces processors) that satisfy stringent mission and safety critical requirements as well as autonomous operation for extremely long durations. Technology development areas include: safe communications, information distribution, multilevel security and multilevel fault tolerance systems. Emphasis will be placed on development of tools, rules, and procedures to facilitate software reuse and allow true and easily configurable multi-mission / multi-role systems for Space Transportation applications. Software technology becomes enabling when one considers the goal of significant reusability. In this context 'reuse' refers to software, not necessarily the hardware. For example, if a navigation software module can be used for a manned Mars mission as well as for a lunar survey, the avoidance of the requirement to verify and validate the new application as thoroughly as the initial application will produce a substantial cost savings. If hardware and software are bundled as a module, the re-verification task is further reduced in scope and cost.

The Vehicle Health Management subelement will address self diagnosis and self compensation for the integrated systems. It includes improvements to reliability, robustness, and failure tolerance of orbit systems whose missions can be characterized by a combination of: extremely long duration, tenuous or nonexistent logistics supply lines, protracted periods of dormancy, long term exposure to earth orbit radiation and changing environment or charged particle/radiation environment of interplanetary space. The approach to Vehicle Health Management will be characterized by shifting built-in test emphasis from line replaceable unit to a lower level and by graceful degradation of function rather than sudden failure. Initial launch system developments will serve as a precursor to development of orbital and planetary systems. Program milestones include: definition and assessment of NASA/DOD/Commercial future requirements for integrated health management; demonstration of a VHM test-bed; insertion of Vehicle Health Management technology into KSC Orbiter launch processing flow; implementation of an on-board integrated system simulation function within a launch system's flight and system management software; and track ETO tasks and determine applicability to Transfer Vehicle Avionics.

Integrated Vehicle Health Management technology has been identified as one of the highest leverage technology targets for any future space effort. A significant up-front investment in basic systems engineering is required to maximize the return of investment in this area. For example, some fundamental trade studies are required to determine optimum functional

allocations and partitioning of VHM between ground and space segments of mission systems. Similarly, simulations and other analysis tools must be developed to facilitate assessment of the cost effectiveness of varying levels of VHM incorporation in expendable, multipurpose, reusable, manned, unmanned, autonomous, supervised, short duration, or long duration vehicles and missions.

The basic technologies that underlie VHM are fairly well understood. What is needed is to investigate fundamental ways of employing these technologies and integrating them into a consistent overall approach to VHM. Thus, policies and procedures governing the insertion of 'smart sensors' (i.e. those devices that perform significant health and status determination and reconfiguration without need for external monitoring) will be developed. VHM will fundamentally change current concepts for spacecraft maintenance and operation. For example, current practice can be categorized as being performance oriented, i.e. the entire design is focused on extracting the highest possible level of performance from the system. For Transfer Systems, a more efficient approach may be to shift to an operational orientation. VHM will allow us to bring some commercial aviation style operational approaches (minimum equipment list, continued nominal operation with failures, performance level derating) to the space operations.

The Advanced GN&C subelement will include an investigation into current and future programs that require the development of advanced navigation, guidance and control laws, efficient computational algorithms, software tools to analyze complex body dynamics, and the application of commercially available analysis and support tools. Advanced GN&C development will address: 1) identification of tools and development of methodologies and models that promote rapid, cost effective development of advanced navigation, guidance, and control models by identifying commercially available design and analysis tools which are suitable to support various Space Transportation Systems 2) advanced navigation, guidance and control law simulation and analysis models which can be utilized for quick evaluation, 3) evaluation of advanced control design and analysis tools using operational and development programs, 4) development of performance requirements for flight certification of sensors, and 5) development of advanced GN&C approaches, algorithms, and integrated functional systems for Lunar/Mars initiative such as landmark tracking and hazard avoidance methods. The Advanced GN&C development will be directed towards advanced navigation, guidance and control laws, efficient computational algorithms, software tools as well as flight certification of advanced sensors.

The Electrical Actuation (EA) subelement will include development of an integrated approach to electric actuator that address the actuation technologies, vehicle performance requirements, and power supply and control technologies. It will enhance system reliability, increase efficiency and reduce weight of actuators through the use of electric motors instead of conventional hydraulic systems. The Electrical Actuation subelement includes: 1) development of fault tolerant EAs and demonstrated performance, reliability, tolerance for the high duty cycles and extended dormant periods, 2) definition and assessment of requirements and systems concepts for the space segments of advanced NASA/Military/Commercial programs, 3) Lab demonstrations of linear motor-direct acting EA and the magnetostrictive actuator servo valve, 4) design and qualification of a family of EAs for service in vehicle system support roles. The Electrical Actuation Program will be directed toward flight control lab aerosurface demonstrations. Designing and qualifying a family of EAs for service in primary and flight critical applications.

Electrical Actuation (EA) technology is enabling for long duration vehicles/ systems where the maintenance and leakage problems of conventional hydraulic systems are unacceptable. The emphasis of EA development for planetary and related vehicles is to reduce weight, power, and volume requirements while increasing reliability. An important dimension to

reliability in this context is the ability to withstand protracted exposure to dormant intervals in a hostile environment without the requirement for constant care and conditioning.

The Power Management and Control subelement will address the development and demonstration of an ultra-reliable, universal, modular, electrical power bus system that serves as a "Power Backbone" to support and integrate "Up" with other avionics subsystems and controls, and "Down" with all sources and loads, which may be paralleled across distributed, intelligent nodes and interfaces. It consist of fault tolerant bus architectures that permit bidirectional energy flow, reconfiguration and multi-node neuron chip controls that employ fuzzy logic neural nets and self healing modules and subsystems. End-to-end systems and components including advanced batteries, flywheels and source/load conversion will be developed. Regenerative fuel cells and related technologies that will facilitate the development of truly closed environmental systems will also be explored as a part of this element.

Technology Contributions to Vehicle Functions:

A summary re-cap of the technology element and subelement contributions to vehicle functions and vehicle related operations is shown in the following matrix. Parts of the avionics systems are involved in operation of most of the vehicle sub-systems. It is not surprising therefore that avionics-related technologies would make contributions over most of the vehicle functions / operations, as shown in the matrix. It includes sensors and data processing as a primary function, along with electric power management / control, and vehicle guidance / navigation / control. The avionics system would be the central core, to bring together the vehicle health management (VHM) provisions for all of the sub-systems. And, these technology efforts will contribute to and enhance methods for maintenance / support of the avionics systems themselves, as well as other sub-systems.

TRANSFER VEHICLE AVIONICS									
Technology Sub-Element	Functions								
	Sensing	Computing/ Data Process	Propulsion & Energy Conv	Aero Maneuvers	GN&C	Support Loads	Mfg.	Grd Test & Process	In-space Assy & Process
• Avionics Architectures		X							
• Adv Software Engrg		X							
• VHM	X	X	X		X	X		X	X
• Advanced GN&C	X	X		X	X				
• Electr Actuator System									
• Power Mgt. & Control	X	X	X					X	X

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Technology Benefits Summary:

Avionic open architectures optimized for transfer vehicle applications which:

- Maximize reuse of components within programs.
- Increase performance, functionality, reliability and fault tolerance.
- Make use of commercial and DOD developments.
- Support autonomy, highly reliable for long flight durations.
- Minimize life cycle costs.
- Modular, scalable, with mature interface standards.
- Support rapid prototyping.

Vehicle Health Management hardware, software components and system architectures which support:

- Autonomy
- Reduced launch processing and operations costs.
- Long exposure to earth orbit radiation, charged particle/radiation environments of interplanetary space.
- Long duration flight.
- Increase vehicle/system self sufficiency

Guidance, Navigation, and Control applications which support:

- Lunar/Mars vehicle transfer, launch and landing requirements
- Low thrust GN&C for nuclear electric propulsion
- Adaptive, failure tolerant
- Optical guidance, landmark navigation

Power Management and Control system architectures, components which support:

- Ultra-lightweight
- Modular
- "Power Backbone" to support and integrate avionic subsystems, sources and loads including actuators
- Advanced fault tolerant architectures with multi-node control, self-healing characteristics
- Fiber optics
- Advanced fully rechargeable batteries, fly wheel, energy storage and smart socket
- Source/load conversion and ground compatible checkout.

4.3.8 Autonomous Landing

Overview:

The objective of the Autonomous Landing Technology Program is to enable safe, accurate, autonomous planetary exploration spacecraft landing in the face of surface hazards and close to areas of mission interest using image-matching navigation and on-board hazard detection systems. Mars and Lunar landings must be achieved safely regardless of surface hazards such as large rocks and steep local slopes, be close to the area of mission interest, and occur without real time ground control. Close collaboration with ETO avionics is necessary. For Earth orbiting and return spacecraft such as PLS and ACRV, landing must be achieved reliably and on short notice.

Current & Related Programs :

Currently, the PLS will use existing Shuttle navigation facilities to perform automatic landings from de-orbit to touchdown.

Autonomous GN&C systems for the next generation of space transports must be capable of long operational periods, be self-contained, and be fully operational after long periods of dormancy for planetary missions. Due to the nonexistence of navigation facilities on the Moon or Mars, a general need exists for image processing and pattern recognition software / hardware that is small, light, fast, low power, and flexible to provide the necessary navigation information. Some specific NASA areas of investigation of autonomous operations are landmark navigation on a planetary surface, and autonomous rendezvous & docking using image processing. No planetary space missions have flown with autonomous GN&C systems that require precision landings on the order of 100 feet; however, the military has solved such problems, well within the accuracy requirements.

NASA is currently observing and / or participating in hardware / software development with military and civilian corporations in the development of image processing and pattern recognition hardware. Also, there have been great strides in autonomous operations in the field of robotics for manufacturing. The areas of pattern recognition used by these robots are currently being investigated for use in autonomous navigation.

Proposed Technology Program for Autonomous Landing:

Autonomous landing capability is required for high success probability of planetary exploration missions. Automatic landing must be achieved while keeping spacecraft resources such as maneuver range, information about the landing environment, navigation references, ability to withstand touchdown, etc., within practical limits.

The two prime areas of importance for safe planetary autonomous landings are precision landing and on-board hazard detection and avoidance.

Precision landing means the ability to land within a predetermined area that is known to be safe. The principal technology needed is accurate navigation with respect to the surface of the planet. When surface beacons are not practical, an alternative is to use image or map-matching navigation of the type used in the Tomahawk cruise missile and the Pershing II missile. The focus of this technology area is on development of an image/map-matching navigation approach that is appropriate to the geometry of the landing site. It must consider the types of surface features present on Mars and the Moon, and be functional in varying levels of illumination.

On-board hazard detection and avoidance is the detection (and vehicle response to subsequent inputs) of a small, safe landing site within an area that is known to be generally safe but may contain localized hazards. The principal technologies needed are the development of a sensor and detection algorithm that can resolve and detect surface hazards so that a safe landing area can be located and utilized in real time. The sensor may be a scanning laser radar and the algorithm may be based on mathematical morphology.

Both precision landing and hazard detection and avoidance systems must be closely coordinated with vehicle design to insure compatibility.

Near-term navigation tasks will concentrate on robust pattern recognition using synthetic discriminating functions, and prediction of reference images from terrain maps for geometry that is more variable than that encountered by the cruise missile. On-board hazard detection work will concentrate on a laser radar using arrays of diode lasers and detector/preamplifier arrays, possibly supplemented with a camera to provide high spatial resolution required for rock detection. Long-term tasks will investigate alternate navigation approaches to determine the minimum level of terrain elevation, radar reflectivity, and other information needed for successful radar image or terrain elevation map-matching navigation. Alternate hazard detection approaches, based on passive computer vision or interferometric imaging, also have some potential. Sensor and system simulations using terrain models and field tests using prototype sensors and actual terrain will be used to evaluate the various approaches.

Tasks include:

- Propose a set of requirements and specifications for the G&C systems and the environment/probable vehicle characteristics.
- Lay out preliminary concepts and designs; conduct trade studies to determine

which lead to the most desirable and realizable systems, considering safety, performance and handling qualities.

- Conduct detailed studies of the most promising automatic and manual systems.
- Investigate feasibility of steerable gliding parachute for landing on Mars.
- Determine abort strategies and attendant design requirements.
- Conduct separation studies (LESC Graphics Work Station).

Performing Center(s): JSC, LaRC

Technology Contributions to Vehicle Functions:

A summary re-cap of the technology element and subelement contributions to vehicle functions and vehicle related operations is shown in the following matrix. Contributions from these technology efforts will be in the three key functions to provide the capability for terrain / hazard avoidance and accurate landings. These basic functions are having the right kind of sensors; providing for algorithms and equipment to process the information properly; contributing to guidance / navigation of the vehicle to the desired landing spot or conditions.

AUTONOMOUS LANDING

Technology Sub-Element	Functions								
	Sensing	Computing/ Data Process	Propulsion & Energy Conv	Aero Maneuvers	GN&C	Support Loads	Mtg.	Grd Test & Process	In-space Assy & Process
• Precision Landing	X	X			X				
• Image/Map Navigation	X	X			X				
• Hazard Detect & Avoid	X	X			X				
• Sensors	X				X				
• Algorithms		X			X				
• Sensor & System Simul	X	X			X				

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4.3.9 Autonomous Rendezvous & Docking (AR&D)

Overview:

The objective of this effort is to develop and integrate the technologies that provide the capabilities to perform autonomous rendezvous and docking operations in space. Rendezvous & docking operations in U. S. space programs to date have been in manned vehicles only, and with direct crew participation with heavy ground support. Development and demonstration of these technologies will permit unmanned spacecraft in Earth, Lunar and planetary orbits to operate without large ground support staffs for mission support (planning, training and conduct), and will support manned spacecraft operations by augmenting the capabilities of the crew to perform rendezvous and docking without ground support.

This capability is needed for Cargo Transfer Vehicle (CTV) operations in support of further SSF build-up and for spacecraft retrieval / servicing, for unmanned upper stage operations, and will be particularly needed for in-space build-up and operations of Lunar / Mars exploration vehicles and in-space supporting facilities.

Current & Related Programs:

In limited preliminary work, overall system requirements have been identified and a sensor trade study has been performed. A graphical playback demonstration was performed in 1990, and preparations are in process for a docking demonstration later in 1991 using existing hardware and AR&D algorithms.

This work will be closely coordinated with the CTV and upper stage planning and development; with work under the Transfer Vehicle Avionics element; and with Vehicle In-Space Assembly / Vehicle Processing elements (part of Operations focused technology program).

Proposed Autonomous Rendezvous & Docking Technology Program:

The proposed Autonomous Rendezvous and Docking program element is aimed at developing integrated guidance, navigation and control; sensors and sensor data processing techniques; and mechanisms to realize an autonomous rendezvous and docking capability.

The goal of this program is to identify requirements for, and to develop and demonstrate an integrated, multi-mission AR&D suite. Key technologies requiring development include Integrated GN&C, sensors and sensor data processing techniques, mechanisms and effectors, and advanced algorithms and techniques. Innovative sensor data processing and sensor fusion concepts will be investigated and selected for demonstration.

This effort will capitalize on NASA's background in manned rendezvous and docking operations and the algorithms, methods, and procedures that support them as well as NASA's man-in-the-loop remotely piloted vehicle background (OMV). Work on AR&D to date will also be used as a baseline.

A schedule function allocation will be performed among the sensor, GN&C, and mechanism elements of the AR&D system. In this manner, an optimized, cost effective capability will be developed.

- Functional requirements for AR&D sensors, mechanisms, and GN&C algorithms will be identified and compared to the current state of the art of each discipline.
 - Preferred approaches to each discipline will be selected and prototyped.
 - Ground demonstration of brass board integrated system and individual elements.
 - Flight experiments and demonstrations in a realistic operational environment against a typical mission scenario.
- Performing Center(s): JSC, LaRC, MSFC.

Technology Contributions to Vehicle Functions:

A summary re-cap of the technology element and subelement contributions to vehicle functions and vehicle related operations is shown in the following matrix. Contributions for autonomous rendezvous / docking technology efforts are in the same three functions as for autonomous landing (e.g., sensing, algorithms / data processing, and guidance, navigation & control). In addition, these efforts will make a key contribution

toward the docking mechanisms by which the vehicles / elements will be joined in space after being mated.

AUTONOMOUS RENDEZVOUS & DOCKING

Technology Sub-Element	Functions								
	Sensing	Computing/ Data Process	Propulsion & Energy Conv	Aero Maneuvers	GN&C	Support Loads	Mfg.	Grd Test & Process	In-space Assy & Process
• Integrated GN&C	X	X			X				X
• Sensor & Data Process	X	X			X				
• Adv Algorithms/Techn's		X			X				
• Mechanisms/Effectprs									
• Systm Grd Testing	X	X			X				
• Flight Test Rqmts	X	X			X				

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Technology Benefits Summary:

This technology capability will enhance and reduce costs of operations in near-Earth space by augmenting manned rendezvous / docking operations without ground support, and by allowing unmanned vehicle operations without large ground support. This capability is required for, and will enable, unmanned planetary exploration missions where injected system mass constraints necessitate docking operations and where communications distances make human remote control impractical.

4.4 Technology Flight Experiments

- 4.4.1 Overview
- 4.4.2 Aeroassist Flight Experiment
- 4.4.3 Cryogenic Orbital Nitrogen Experiment
- 4.4.4 Solar Electric Propulsion Experiment (SEPS)
- 4.4.5 Potential Future Augmentations
 - 4.4.5.1 Cryogenic Orbital Hydrogen Experiment
 - 4.4.5.2 High Energy Aerobraking Flight Experiment

4.4.1 Overview

The objective of the Technology Flight Experiments program is to enable safe, reliable and cost-effective transportation for cargo and personnel to Earth orbit, beyond and return to Earth. This includes validation for technologies supporting initial lunar transfer vehicle/lander, SEP upper stage, Space Shuttle Evolution, NLS evolution for initial lunar mission, evolution lunar transfer vehicle/lander, NEP upper stage, AMLS, Mars nuclear space transfer vehicle/lander, and NLS evolution for initial Mars mission. Earth-to-orbit and space transportation technologies will be demonstrated and critical flight research data will be collected through the implementation of in-space technology experiments that support all vehicle systems.

In-space experiments for ETO and Space Transportation systems will be developed and conducted that support ground-based technology developments and promote timely transfer of the technology to the users. The program will provide for the advocacy, development and integration for NASA identified experiments which support the development of critical technologies.

4.4.2 Aeroassist Flight Experiment

Overview:

The objective of the Aeroassist Flight Experiment is to flight validate critical aerocapture design requirements and environment. The AFE is a Shuttle-deployed free-flying spacecraft being developed by NASA to provide flight data for the design of future Aeroassist Space Transfer Vehicles (ASTV) for Lunar, Mars, or geosynchronous return vehicles. Four NASA centers are involved in the Project with MSFC responsible for overall project management, carrier vehicle development, and spacecraft integration. The Langley Research Center and Ames Research Center are responsible for development of major experiments. LaRC is also responsible for the integrated science requirements. The Johnson Space Center is responsible for the aerobrake design and fabrication, as well as selected experiment development.

Current & Related Programs:

The AFE is being developed to provide flight data for the design of future ASTVs. Aeroassist is defined to be a generic term encompassing various aerodynamic maneuvers in which a vehicle enters and exits the atmosphere to achieve braking without making a complete entry. Many opportunities exist to use aeroassist in future missions such as Lunar, Mars, and geosynchronous return missions. The use of aeroassist significantly enhances the payload-carrying performance of a space transfer vehicle.

The AFE will investigate critical vehicle design technology issues applicable to aeroassist vehicles. The aerodynamic maneuvers will occur in the upper regions of Earth's atmosphere at or near geosynchronous return velocities, producing aerothermodynamic environments that cannot be simulated in ground facilities or modeled using existing analytical techniques. It is necessary, therefore, to obtain critical aerodynamic, aerothermodynamic, and environmental data from flight simulation. These data will be used as benchmarks for the verification of experimental and computational flowfield techniques in the nonequilibrium chemistry flight regime. The AFE will carry a number of experiments designed to gather the required data on vehicle atmospheric flight environments, such as the radiative and convective heating rates experienced, and on vehicle design technologies, such as thermal protection system performance, aerodynamics, and flight control.

Understanding the aerothermodynamic environment is critical to the design of light-weight heatshields for ASTV since this parameter will dictate the selection of materials and material thickness of the heatshield. Therefore, the AFE is being designed to achieve this basic objective with a heatshield sufficiently instrumented to obtain data that will permit critical ASTV projected environments to be measured.

The AFE will be flown to, and recovered from, low Earth orbit by the space shuttle Orbiter. The AFE will be released on orbit at a nominal altitude of 160 nautical miles, and after an appropriate on-orbit check out will accelerate downward into the Earth's atmosphere to a velocity of 33,800 feet per second at atmospheric entry, which produces the requisite nonequilibrium chemistry dominated flowfield.

The perigee of the spacecraft's trajectory occurs at an altitude of approximately 250,000 feet above the Earth's surface. The AFE program objectives are designed to be accomplished in a single flight. Launch is currently scheduled for July 1996.

Proposed Technology Program:

The proposed technology program is the current program. While the AFE project provides funding to the ground-based testing activities, some computational fluids dynamics analysis and the new thermal protective materials development are funded by OAET as part of their basic research and technology program.

Summary of AFE Program Benefits:

In meeting its mission objectives, the AFE program will resolve the major questions about radiative heating at hypersonic velocities. It will determine the effects of wall catalysis. This is very important for designing vehicles capable of traveling at high speeds in the upper atmosphere where nitrogen and oxygen atoms may play important roles in heating due to recombination of the wall of the aerobrake. Advanced TPS materials will be evaluated. Several different thermal control coatings will be tested on the basic TPS tiles. The wake flow and base heating will be defined, and the ability to control the vehicle in its flight through the atmosphere will be assessed. The new data base produced from the AFE program will provide a basis to develop and verify codes to be used in the computer design of other hypersonic vehicles, including the ASTV space transportation system.

4.4.3 Cryogenic Orbital Nitrogen Experiment

Overview:

The objective of the CONE project is to gather 0-g flight data required to validate the cryogenic fluid analysis tools necessary to design LN₂ and LOX pressure control and liquid transfer systems for SSF and Space Transfer Vehicles as well as extrapolate, where possible, the basic data to partially validate LH₂ models. The goal is to develop and fly a subscale cryogenic fluid system to provide low-g data necessary for the partial model validation of the active TVS and nonvented liquid transfer analytical models being developed in the R&T Base Cryogenic Fluid Management program. The flight experiment will also provide the low-g demonstration of critical components and processes including passive TVS, LAD expulsion and fill, autogenous tank pressurization, pressurant generation, thermal subcooling, and fluid dumping. Liquid nitrogen will be used to reduce safety concerns and thus limit the applicability of the results to future LOX/LN₂ systems.

Current & Related Programs:

There is no current program. This is a proposed potential element to start in FY93. This program will be closely coordinated with the Cryogenic Fluid Management Base R&T program, the Cryogenic Fluid Systems focused technology program and provide inputs for the Cryogenic Orbital Hydrogen Experiment. Efforts will be made to provide synergy with the Nuclear Thermal Propulsion, Space & Surface Operations, and other programs applying cryogenic fluids for liquid oxygen and liquid nitrogen for life support.

Proposed Technology Program:

The technical objectives fall into three subelements: pressure control, liquid supply and liquid transfer. In pressure control, the objectives are to extend cryogenic data to low-g regimes and to reduce the required mixer power by two orders of magnitude. Under liquid supply, the objective is to demonstrate 0-g acquisition with cryogen. The liquid transfer objectives are to partially validate 0-g models for tank chilldown/fill and to demonstrate 0-g no-vent fill capability.

LeRC is the lead Center for CONE project management, program requirements, design, analytical model development, data analysis and model validation. MSFC is a participating Center with input to program requirements, system test and verification requirements, system-level testing of flight hardware and STS integration.

Summary of CONE Program Benefits:

Cryogenic fluid technologies offer the potential to store and transfer cryogenic fluids in low-Earth orbit. On-orbit resupply of spacecraft and space vehicles will result in significant reduction of required fluid margins, mass to low-Earth orbit and in added mission flexibility. The objective of CONE is to validate the basic technologies within the Cryogenic Fluid Systems program required to store, supply and transfer subcritical cryogenic liquids in the low-gravity environment of space in an efficient, safe and reliable manner. CONE will be the first demonstration of the required technologies that will enable on-orbit storage and resupply operations for future spacecraft and space transportation vehicles required for space exploration and space transportation vehicles required for space exploration and for low-Earth to geostationary Earth orbit missions.

4.4.4 Solar Electric Propulsion System (SEPS) Flight Experiment

Overview:

The objective of the Solar Electric Propulsion System Flight Experiment program is to validate ion and hydrogen propulsion and advanced photovoltaic solar array (APSA) and related photovoltaic technologies readiness via flight test. The space test will be applicable to a broad set of mission types and users. Two classes of flight tests are proposed in a paced program to assure application of SEPS-precursor sub-scale technology validations to support SEPS technology readiness by 1997. There will be demonstrations of functional SEPS where modest mission goals are achieved in addition to system level technology demonstrations in order to support IOC by 2002.

The mission applications for the Solar Electric Propulsion Experiment are hydrogen arcjets and inert gas ion propulsion for earth-space orbit raising and inert gas ion propulsion for planetary missions.

Major milestones include subscale APSA design, ion propulsion ground validated, hydrogen arcjet systems ground validated, hydrogen cryogenic management concept ground validated, propulsion systems integrated on spacecraft launch vehicle, launch pad modifications for hydrogen, and actual launch.

Participants include LeRC as the lead element and responsible for propulsion, JPL as supporting Center and responsible for the solar array, industry with in-kind support responsibilities and DOD responsible for the launch, spacecraft and operations.

Current & Related Programs:

The basic technology for SEPS is worked in the R&T Base program. This experiment is a proposed potential new-start for 1994.

Proposed Technology Program:

Two classes are flight tests are proposed in a paced program to assure applications

of SEPS. The first class involves precursor sub-scale technology validations to support SEPS technology readiness by 1997. The second class includes demonstrations of functional SEPS where modest mission goals are achieved in addition to system level technology demonstrations and to support SEPS IOC by 2002. For both classes, attempts will be made to exploit opportunities to leverage non-NASA contributions and to maximize the relevance of the space test to a broad set of mission types and users.

A simple space test on a free flyer is proposed which would demonstrate 30 centimeter inert gas ion propulsion (operated in a derated condition and an arcjet operated on cryogenically stored hydrogen. Power is assumed provided by a derated APSA photovoltaic array. The launch vehicle and spacecraft are assumed provided by an external group (DOD ELITE program). Sufficient propellant is assumed to operate the arcjet and ion thrusters for over 500 hours and 4000 hours, respectively.

Critical events:

- Propulsion ground validated
- H₂ arc jet systems ground validated
- H₂ cryogen management concept ground validated
- Propulsion systems integrated on spacecraft
- Launch vehicle and Launch Pad mods for H₂ complete
- Launch

Performing Center(s): LeRC, JPL

Summary of Program Benefits:

The Solar Electric Propulsion Experiment will provide significant propellant savings for geosynchronous, and equivalent, missions electric propulsion systems. These savings will enable increased payload mass fraction and reduced launch vehicle costs.

4.4.5 Potential Future Augmentation Elements

There are two major flight technology development/validation experiments which might be considered in the future. The Cryogenic Orbital Hydrogen Experiment would be somewhat similar in nature to the CONE with cryogenic hydrogen instead of oxygen. The High Energy Aerobraking Flight Experiment addresses a higher energy entry than the AFE.

4.4.5.1 Cryogenic Orbital Hydrogen Experiment

The objective of the COHE program is to address critical fluid management technologies via system demonstration and space experimentation to validate analytical models and to demonstrate critical components and processes. Technical subelements include pressure control (active and passive system demonstrations), liquid supply (capillary acquisition device demonstration and autogenous pressurization system demonstration), liquid transfer (validation of zero-g models for tank chill down and no-vent fill) and fluid handling (liquid dumping in zero-g and mass gaging system evaluation). This program will be closely coordinated with the Cryogenic Fluid Management Base R&T program, the Cryogenic Fluid Systems focused technology program, and the Cryogenic Orbital Nitrogen Experiment. Efforts will be made to provide synergy with the Nuclear

Thermal Propulsion, Space and Surface Operations, and other programs applying cryogenic fluids for liquid oxygen and liquid nitrogen for life support. Participants would include LeRC and MSFC.

The goal of this program is to develop and fly a subscale fluid system to provide low-g data necessary for the final model validation of a majority of the analytical models being developed in the Base R&T Cryogenic Fluid Management program. The flight experiment will also provide the low-g demonstration of critical components and processes. Technologies to be addressed include passive TVS, active TVS, LAD expulsion and fill, autogenous tank pressurization, pressurant generation, thermal subcooling, nonvented liquid transfer, and fluid dumping. Liquid hydrogen will be used because of its prominent use as a propellant and its challenging fluid management requirements. The component demonstrations and validated models will therefore be applicable to all future missions employing cryogenic fluid systems.

4.4.5.2 High Energy Aerobraking Flight Experiment

The objective of the High Energy Aeroassist Flight Experiment is to extend flight data significantly beyond the levels of the Aeroassist Flight Experiment into the regimes of Mars aerocapture and Earth return from Mars. The purpose would be to reduce the level of design uncertainty so that performance requirements can be met with a high degree of confidence and at the least cost. Experiments would assess: radiative heating, wake flow, and base heating environments, CFD model verification, TPS and thermal structure performance, CFD model validation, TPS and thermal structure performance and adaptive guidance performance.

HEAFE will build upon the results of the AFE program as a follow-on. The Aeroassist Flight Experiment was designed to simulate the flight environment of a return from geosynchronous orbit. However, this environment is close enough to the Lunar return conditions to provide validation of CFD models and thermal protection materials for the Lunar missions. The flight environments for the Mars aerocapture and the Earth return from Mars are quite different and likely to be considerably more severe than the AFE environments, thereby requiring additional flight data for those missions. The Aerobraking Technology Project would provide the initial requirements, justification and system concepts for this project.

The flight regimes for Mars aerocapture and Earth return vary greatly depending on the mission design and the year of mission opportunity. However, these regimes are probably significantly more severe than our prior flight experience (including AFE and Lunar aerobraking vehicles), especially for the low trip time missions desired for manned missions. Flight data will be important for validation of aerothermodynamic models including definition of radiative heating on the forebody and wake closure and heating on the afterbody, demonstration of high heating rate TPS, demonstration of real-time adaptive guidance, as well as the demonstration of an integrated aerobraking system. This flight test is envisioned to be an expansion of the AFE concept to a significantly higher Earth entry velocity utilizing the same type of flight instrumentation and operational concept.

CHAPTER 5

IMPLEMENTATION PROCESS

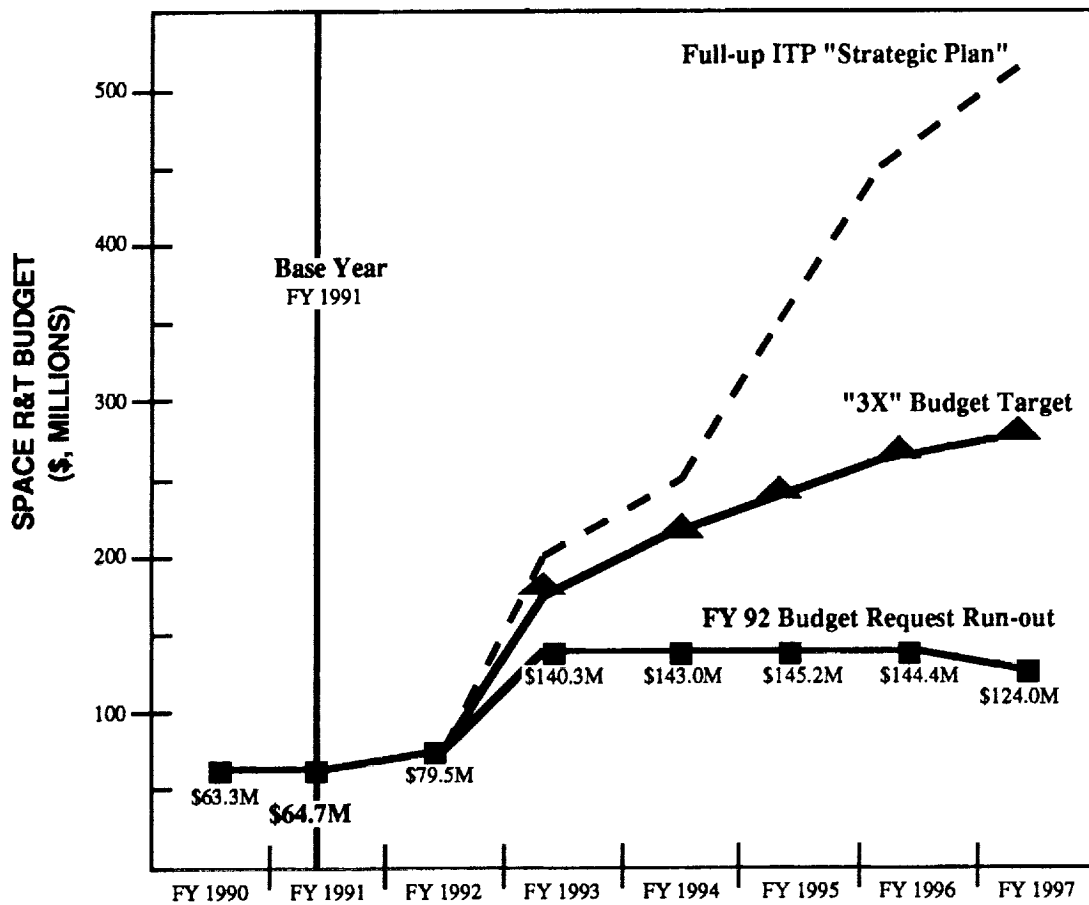
The Transportation Technology Team has developed a strategic plan for the technology development required to support on-going and future civil space missions. The SSTAC has conducted its large-scale annual review of the Space R&T program. It has provided feedback which has been considered in the preparation of this report on the transportation technology program. The strategic plan, presented in this report, will be updated annually as the transportation technology user offices and the space transport industry update their technology needs/requirements. As this document goes to press, several significant events have been or are about to be announced. These events include a conference committee in Congress finalizing the NASA FY 1992 budget for the President's signature, the announcement of the formation of a new Office of Exploration, another announcement naming a new Office of Space Systems Development and a revised definition of roles and missions for the various NASA Centers expected to be announced in the near future by the Associate Administrator. With the announcement of the transfer of space exploration to the newly announced Office of Exploration, it is expected that OAET will revert to its former name of the Office of Aeronautics and Space Technology (OAST). These changes will be reflected in an updated plan which should be released by late summer 1992 and will include a proposed FY 1994 program plan. It will also reflect user requirement updates expected from the OSSA Woods Hole meetings this summer and any changes to the SEI technology needs as necessitated by the resolution of any differences between the Synthesis Group and the current Office of Space Exploration as well as any deltas that may be introduced by the recently announced Office of Exploration to be organized in the coming weeks or months.

In June of this year, the Space Systems & Technology Advisory Committee, The SSTAC Aerospace R&T Subcommittee, the National Research Council Aeronautics and Space Engineering Board, and selected individuals from the Space Science and Applications Advisory Committee, the Aerospace Medicine Advisory Committee, the NRC Space Studies Board, the Department of Defense, the Department of Transportation, the Department of Commerce, the Department of Energy and the Aerospace Industries Association convened at Vienna, Virginia to review the OAET Space R&T Integrated Technology Program. Figure 5-1 illustrates the FY 1992 budget request run-out contrasted with the "3X" budget target and the funding required to fully implement the strategic plan.

Additionally, the Agency has now worked through the FY 1993 budget preparation process. The President will present his FY 1993 budget to the Congress in February, 1992. At that time, the Transportation Technology Team will add an addendum to this report that includes that FY 1993 budget with its runout as it pertains to the Transportation Technology Program as well as the actual FY 1992 program.

To fully implement this strategic plan is clearly beyond the NASA Space R&T fiscal resources. Therefore, one purpose of this plan is to serve as a mechanism for coordination with other government and industry plans to synergistically pursue technology development in areas of common interest.

Figure 5-1
TRANSPORTATION TECHNOLOGY BUDGET IMPLICATIONS



¹Office of Space Flight (NASA). 1991. *Office of Space Flight Technology Requirements. Definition and Planning for Coordinated Programs.*

APPENDIX A TRANSPORTATION TEAM MEMBERS

Co-Chair: David Stone/NASA Headquarters OAET
Co-Chair: Gabriel Wallace/NASA Marshall Space Flight Center

Member: Robert Davies/NASA Headquarters OSF
Member: James Kelley/NASA Jet Propulsion Laboratory
Member: Phil Deans/NASA Johnson Space Center
Member: Raymond Evans/NASA Kennedy Space Center
Member: William Pyland/NASA Langley Research Center
Member: Larry Diehl/NASA Lewis Research Center
Member: Frederick Huffaker/NASA Marshall Space Flight Center

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APPENDIX B

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APPENDIX C

List of Acronyms/Abbreviations

ACRV	Assured Crew Return Vehicle
ADP	Advanced Development Program
AFE	Aeroassist Flight Experiment
AI	Artificial Intelligence
AIA	Aerospace Industries Association
Al-Li	Aluminum Lithium
AMLS	Advanced Manned Launch System
APS	Auxiliary Propulsion System
APSA	Advanced Photovoltaic Solar Array
ARAD	Autonomous Rendezvous & Docking
ARC	Ames Research Center
ARS	Advanced Recovery System
ARTS	Aerospace R&T Subcommittee
ASEB	Aeronautics and Space Engineering Board
ASTV	Aeroassist Space Transfer Vehicle
ATS	Actuator Test Set
BIT	Built-In Test
BTU	British Thermal Unit
CFD	Computational Fluid Dynamics
CFS	Cryogenic Fluid Systems
CID	Computer Integrated Design
CIM	Computer Integrated Manufacturing
COHE	Cryogenic Orbital Hydrogen Experiment
CONE	Cryogenic Orbital Nitrogen Experiment
COMSTAC	Commercial Space Transportation Advisory Committee
CRT	Cathode Ray Tube
CSTI	Civil Space Technology Initiative
CTF	Component Test Facility
CTV	Cargo Transfer Vehicle
DDT&E	Design, Development, Test and Evaluation
DOD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
DSN	Deep Space Network
EA	Electrical Actuation or Electrical Actuator
ELV	Expendable Launch Vehicle
EHA	Electrohydrostatic Actuator
EMA	Electromechanical Actuator
EMCS	Electromechanical Control System
ESA	European Space Agency
ETO	Earth to Orbit
FDIR	Fault Detection, Isolation and Recovery
FS	Flight Systems
ft	feet
g	Gravity
G&C	Guidance & Control
GEO	Geostationary Earth Orbit
GN&C	Guidance, Navigation and Control
GPS	Global Positioning System

GRC	General Research Corporation
H ₂	Hydrogen
HEAFE	High Energy Aeroassist Flight Experiment
HLLV	Heavy Lift Launch Vehicle
ICHM	Integrated Controls & Health Management
IFOG	Interferometric Fiber-Optic Gyro
IME	Integrated Modular Engine
INEL	Idaho National Engineering Laboratory
IOC	Initial Operational Capability
I _{sp}	specific impulse
IR&D	Internal Research & Development
ITP	Integrated Technology Plan
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
K	Kelvin
kg	Kilogram(s)
kH	kiloHertz
klbf	kilo-pounds force
km	Ki
KSC	Kennedy Space Center
LAARS	Low Attitude Retro-Rocket System
LAD	Liquid Acquisition Device
LANL	Los Alamos National Laboratory
LaRC	Langley Research Center
lb	pound(s)
L/D	Length to Diameter Ratio
LED	Light Emitting Diode
LEO	Low-Earth Orbit
LeRC	Lewis Research Center
LEV	Lunar Excursion Vehicle
LH ₂	Liquid Hydrogen
LN ₂	Liquid Nitrogen
LOX	Liquid Oxygen
LRU	Line Replacement Unit
LTV	Lunar Transfer Vehicle
MEV	Mars Excursion Vehicle
Mg	Magnesium
MLI	Multilayer Insulation
MMH	Monomethylhydrazine
MSFC	Marshall Space Flight Center
mT	metric Tonne
MTV	Mars Transfer Vehicle
MW	MegaWatt
MW _e	MegaWatts (energy)
NASA	National Aeronautics and Space Administration
NASP	National Aerospace Plane
NDE	Nondestructive Evaluation
NEP	Nuclear Electric Propulsion
NLS	National Launch System
NPO	Nuclear Propulsion Office
NRA	NASA Research Announcement
NRC	National Research Council
NSTS	National Space Transportation System

NTO	Nitrogen Tetroxide
NTP	Nuclear Thermal Propulsion
NTR	Nuclear Thermal Reactor
O ₂	Oxygen
OAET	Office of Aeronautics, Exploration & Technology
OAST	Office of Aeronautics and Space Technology
OE	Office of Exploration
OM/AC	Orbital Maneuvering and Attitude Control
OMB	Office of Management and Budget
OMS	Orbital Maneuvering System
OMV	Orbital Maneuvering Vehicle
ORNL	Oak Ridge National Laboratory
OSE	Office of Space Exploration
OSF	Office of Space Flight
OSO	Office of Space Operations
OSSA	Office of Space Science and Applications
P _e	Power (electrical)
PLS	Personnel Launch System
PMAC	Power Management and Control
PSI	Pounds per Square Inch
RCS	Reaction Control System
ROM	Rough Order of Magnitude
R&T	Research and Technology
SATWG	Strategic Avionics Technology Working Group
SDIO	Strategic Defense Initiative Office
sec	Second(s)
SEI	Space Exploration Initiative
SEPS	Solar Electric Propulsion System
SNL	Sandia National Laboratory
SOA	State-of-the-Art
SRM	Solid Rocket Motors
SRT	Space Research & Technology
SSAAC	Space Science and Applications Advisory Committee
SSC	Stennis Space Center
SSF	Space Station Freedom
SSFP	Space Station Freedom Program
SSME	Space Shuttle Main Engine
SSTAC	Space Systems and Technology Advisory Committee
SSTO	Single Stage to Orbit
STME	Space Transportation Main Engine
STS	Space Transportation System
STV	Space Transfer Vehicle
TPS	Thermal Protection System
TRL	Technology Readiness Level
TTB	Technology Test Bed
TVC	Thrust Vector Control
TVS	Thermodynamic Vent System
USAF	United States Air Force
USSR	Union of Soviet Socialist Republics
VHM	Vehicle Health Management
WBS	Work Breakdown Structure

END DATE MAY 18, 1993

